Low-Swirl Combustion - A Novel Concept for Heating and Power Generation

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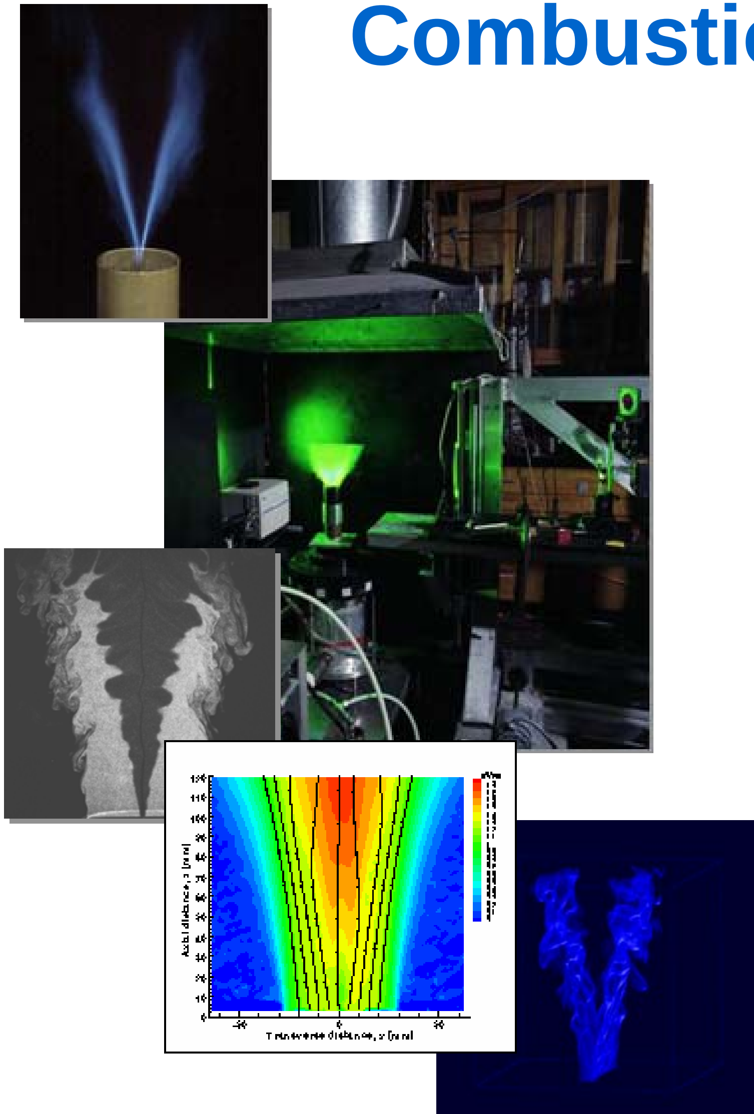
LBNL Combustion Research Emphasizes Combustion Fluid Mechanics



- **Motivation:** Turbulence controls flame processes in all combustion systems
  - Efficiency, emissions, safety
  - Important unresolved problem of physical science
- **Needs:** Fundamental understanding of flame/turbulence interaction
  - Turbulent combustion theories
  - Computational tools
  - Advanced burner/combustor designs
- **Focus:** Lean premixed turbulent combustion

Presentation Outline

- Conventional flame stabilization
- Low-swirl flame stabilization
- Engineering of a practical burner
- Adaptation to heating systems
- Adaptation to gas turbines (paper presented at 30th International Combustion Symposium)
- Outlooks

Conventional Flame Stabilization

Lean Premixed Combustion as a Passive Pollution Prevention Technology

- **Opportunity**
  - **Low NO_x due to low flame temperatures**
  - **Can meet most stringent air quality rules in California (NO_x < 9 ppm @ 3% O_2)**
- **Barriers**
  - **Flame stabilizer or holder dictates operating envelope**
  - **Combustion oscillations**
  - **Sensitivity to mixture inhomogeneity and compositions**

Some Conventional Flame Stabilizers

Piloted Flame

Bluff Body Holder

Bluff Body + Swirl

Issues with Conventional High-Swirl Stabilization Methods

- **Dominated by large recirculation zone**
  - hot combustion products trapped in the vortex continuously igniting the surrounding swirling reactants
  - fragmentation of the flame fronts due to high turbulence shear stresses
  - nonlinear interactions between fluid mechanics & combustion processes coupled with vortex breakdown and precessing vortex core
- **Instabilities leading to premature blowout**
  - Onset of intermittent flame detachment precursor to blowout
- **Instabilities leading to oscillations**
  - Coupling of the heat release & chamber acoustics
- **Mitigation of instabilities & oscillations required at ultra-lean conditions**
  - Staged rich pilot
  - Active feedback control
  - Catalytic pilot or combustor

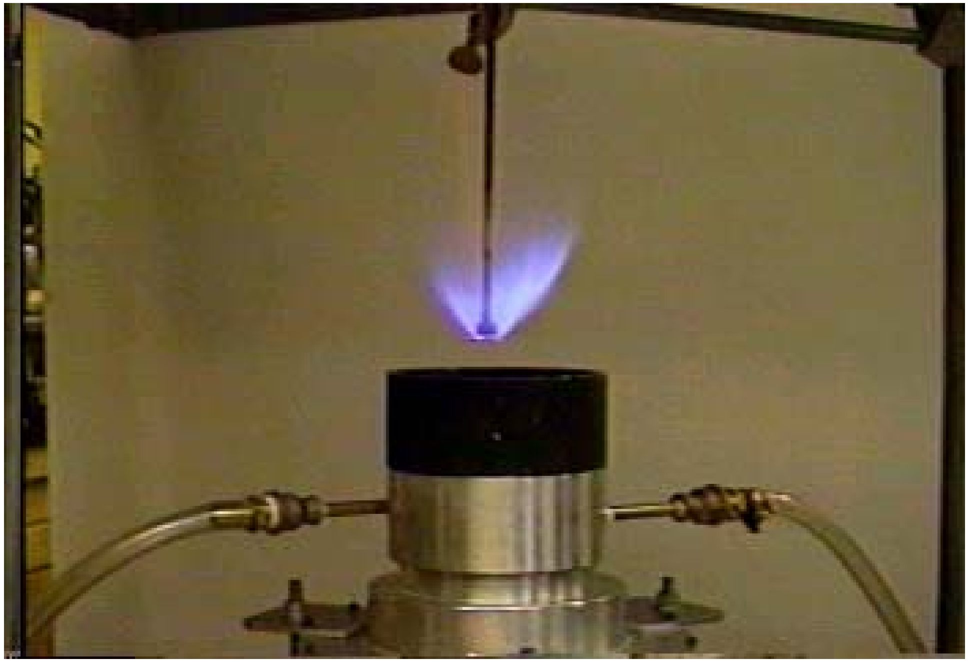
Low-Swirl Flame Stabilization

Premixed Flames Stabilized by Low Swirl

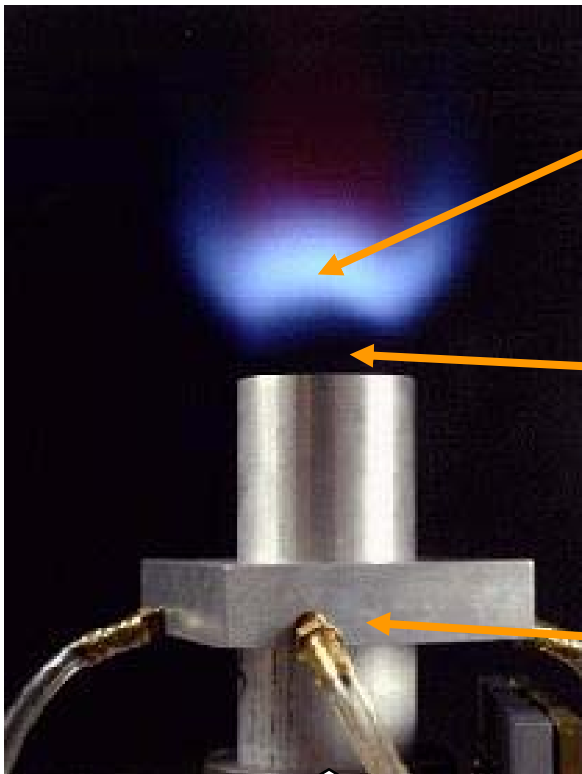
- **Novel concept discovered in 1991 for DOE-BES works**
  - **Counter to conventional high swirl methods**
  - **Introduced a turbulent combustion research topic**
- **Scientific Interest**
  - **New flame stabilization principle**
  - **Challenging problem for models and simulations**
  - **Excellent laboratory research tool**
- **Technological Interest**
  - **Capability to support stable ultra-lean flames**
  - **Simple design**
  - **US Patent granted 1998**

Demonstration of Transition from Bluff-Body Stabilization to Low-Swirl Stabilization

- **By introducing a very small amount of swirl air through the two small tangential jets (swirl number S ≈ 0.6), this video shows that the flame can transition to free propagation with the bluff body removed**



Principle of Low-Swirl Flame Stabilization Method



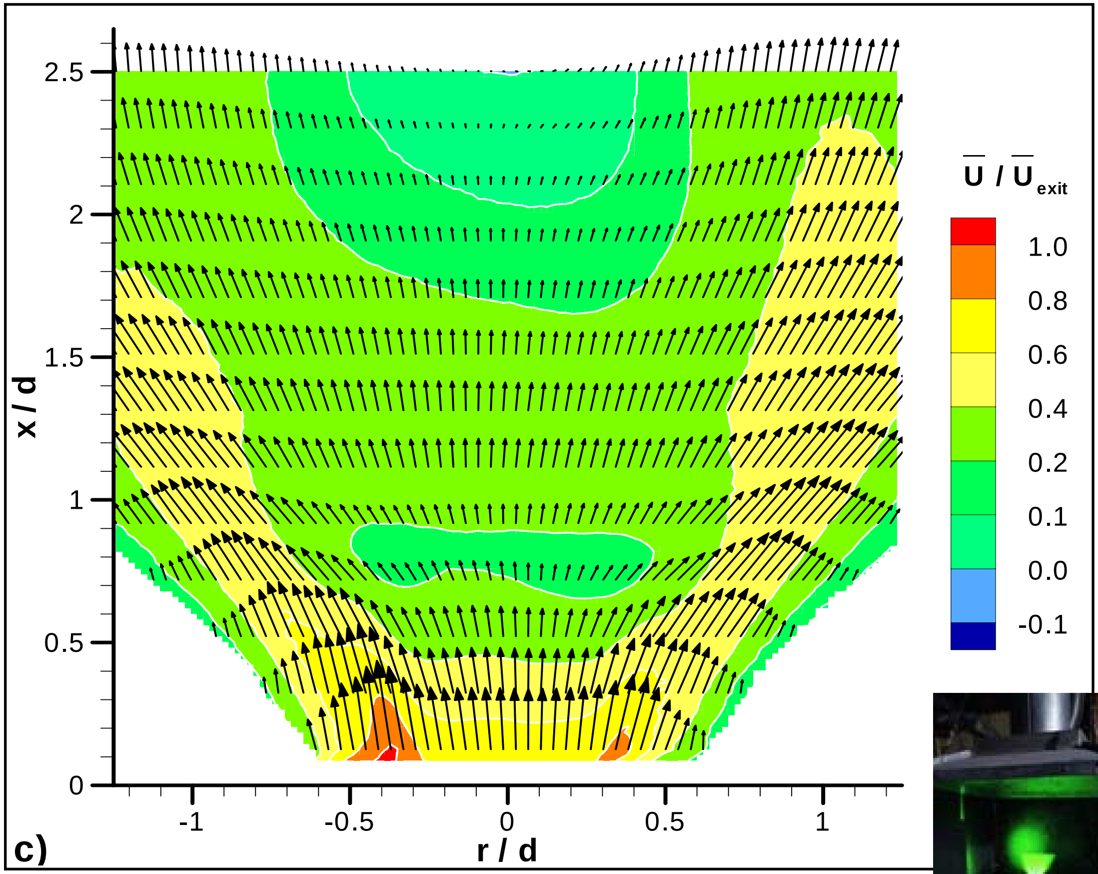
Propagating against the divergent flow, the flame settles where the local velocity equals the flame speed

Flow divergence (generated by low-swirl) above the burner tube is the key element for flame stabilization

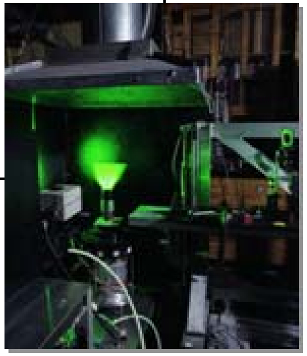
Small air jets swirl the perimeter of the fuel/air mixture but leave the center core flow undisturbed

Fuel/Air mixture

Flame Stabilization Mechanism Studied by Laboratory Experiments



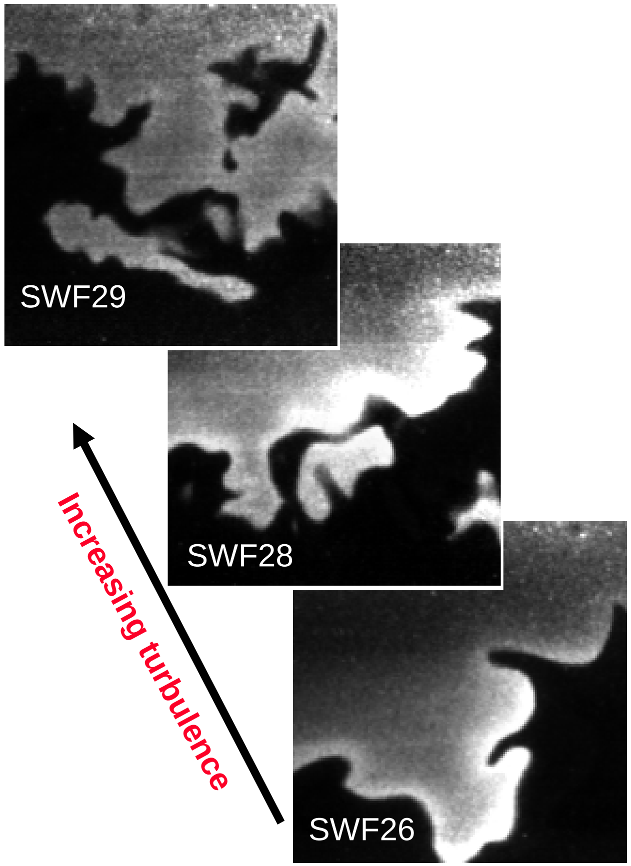
LSB flowfield from particle image velocimetry



- **Flowfield devoid of strong recirculation and high shear**
- **Self-adjusting mechanism**
  - **withstands fluctuations in velocity, turbulence, mixture compositions and mixture inhomogeniety**
  - **flashback conditions predictable**

LSBs as a Research Tool

- **LSBs support premixed turbulent flames under a wide range of turbulence and mixture conditions**
  - **Allows flame to interact with full turbulence spectrum**
  - **Provided clear demonstration of turbulent flame speed correlation with turbulence intensity**
  - **Showed evolution of flame generated turbulence and flow dynamics through the flame brush**
  - **Verified new premixed turbulent flame regime diagram by the use of special turbulence generator**
  - **Related turbulent burning rate to flame speed**

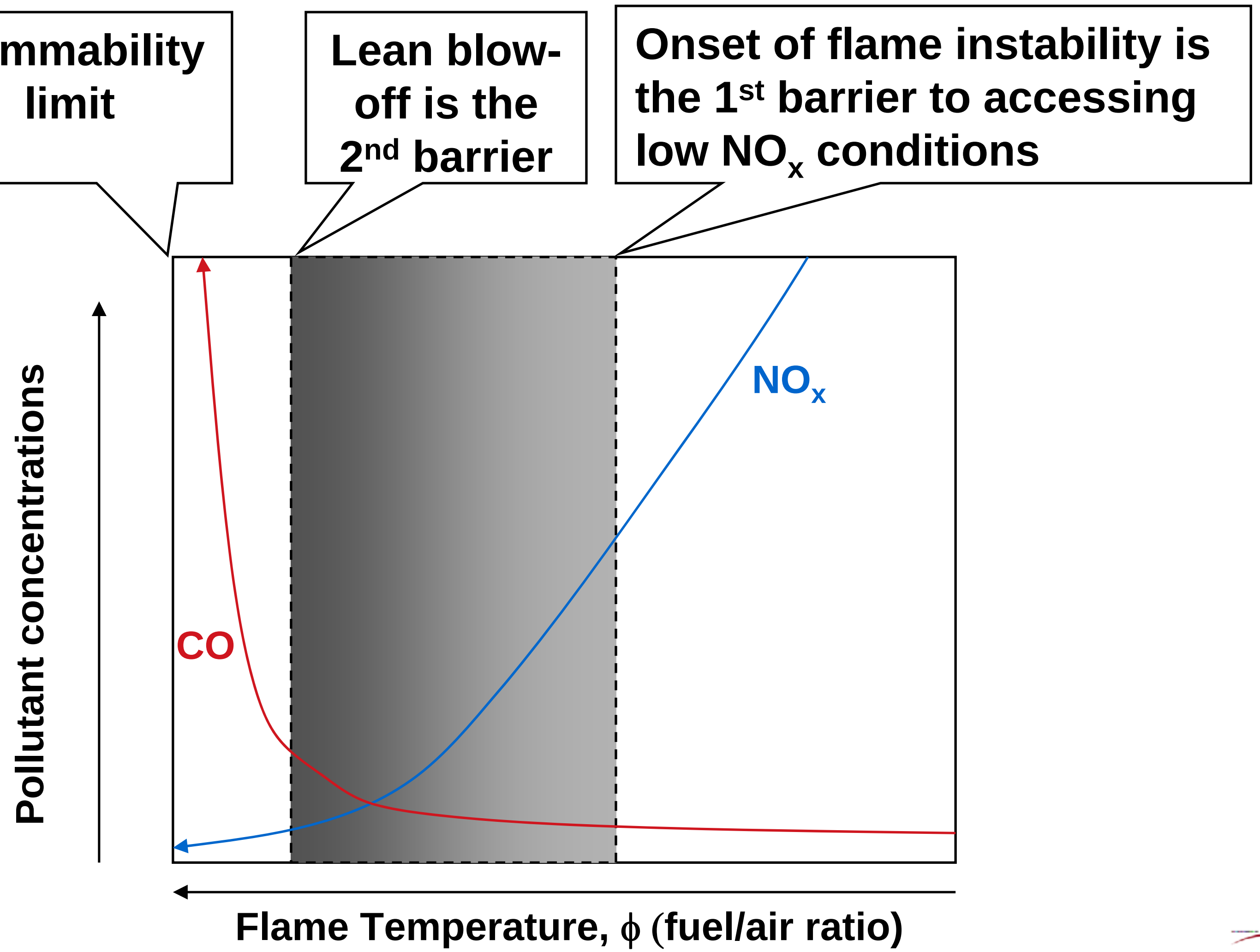


Using OH-PLIF on a specially design LSB we verified a new flame regime for premixed turbulent flames

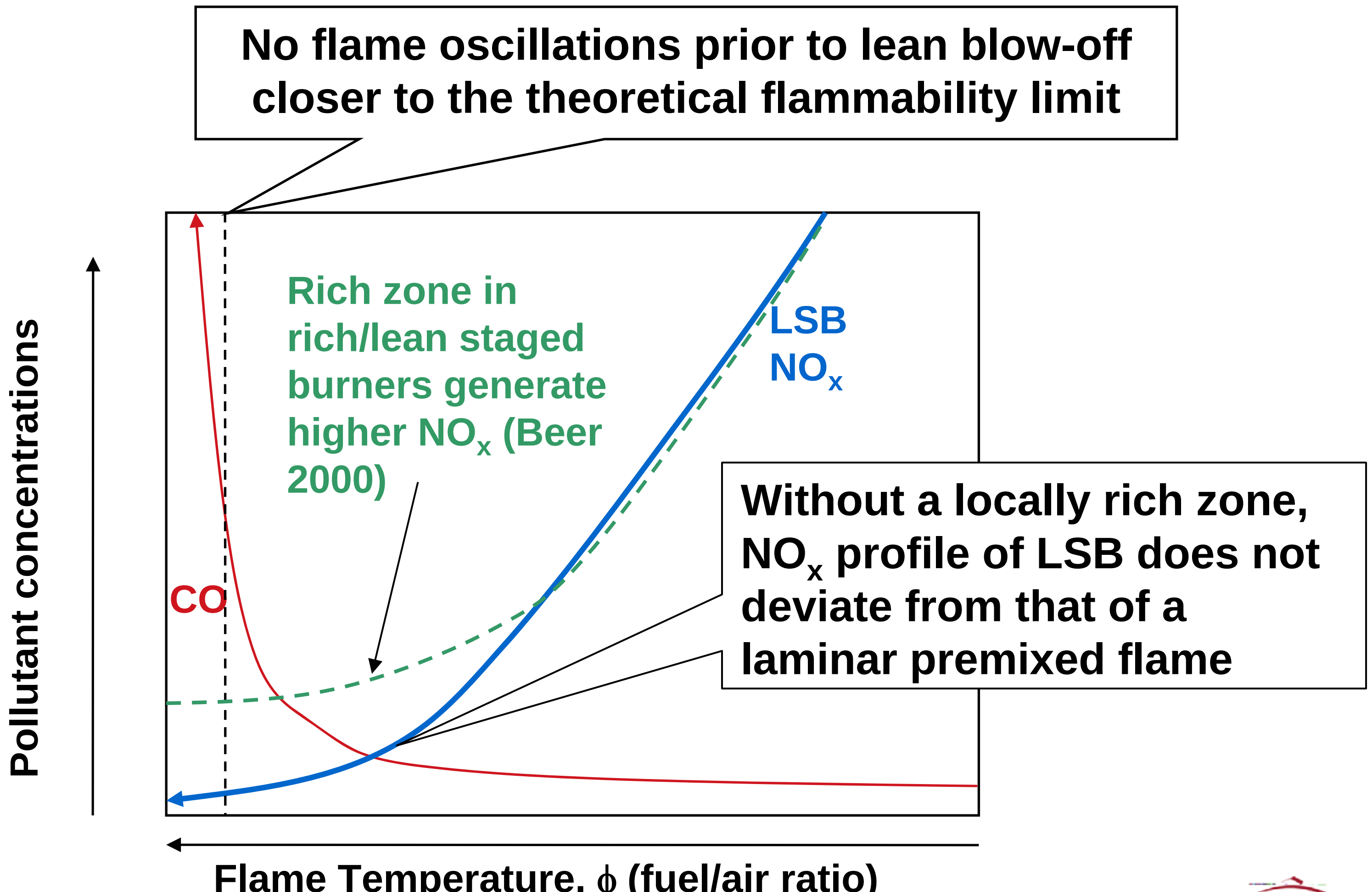
High Swirl vs. Low Swirl for Flame Stabilization

	High Swirl	Low Swirl
Principle	Vortex traps hot products and continuously ignites fresh mixtures	Flame propagates freely in a turbulent divergent flow without recirculation
Flame/ turbulence interaction	Flame developing in high shear region leads to flame fragmentation and occasional detachment	Flame developing in isotropic turbulence with low shear stresses is less prone to fragmentation
Instability	Characteristic frequencies associated with recirculating vortex	No distinct characteristic frequency due to absence of recirculation

Instabilities & Premature Lean Blow-off Are Barriers to Accessing Low Emissions



Low-Swirl Combustion Has More Desirable Instability & Lean Blow-off Characteristics

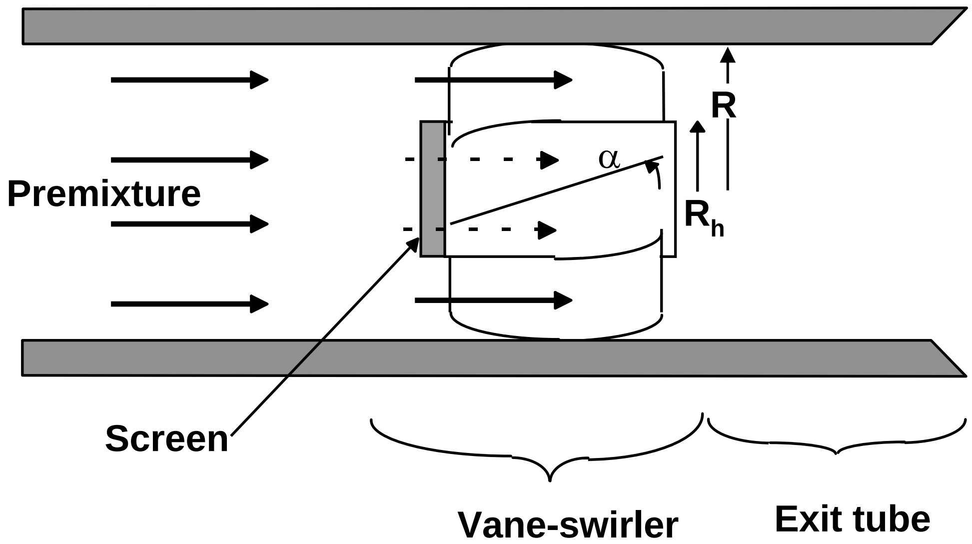


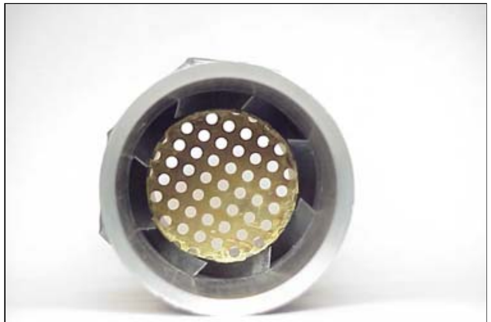
Engineering of a Practical Burner

A Simple Vane-Swirler is Essential for Practical Uses

- **Motivation**
  - **Two stage air-jet LSB is too elaborate for most products**
    - **requires separate control of swirl air and premixture**
    - **needs source of auxiliary air**
- **Goal**
  - **Develop a single stage burner with a vane-swirler that generate the same divergent flow as in a air-jet LSB**
- **Challenges**
  - **no prior background research available**
  - **most swirlers designed to generate robust recirculation**
- **Approach**
  - **Use laser Doppler velocimetry as a tool to develop a vane swirler that produces the characteristic divergent flowfield**

Vane-Swirler Developed for LSB





Top view of patented vane-swirler

- Open center channel allows a portion of flow to bypass swirl vanes
- Angled guide vanes induce swirling motion in annulus
- Screen balances pressure drops between swirl and centerbody
- Patent granted in 1999

First Practical LSB Engineered for 50 – 150 KBtu/hr Pool Heaters

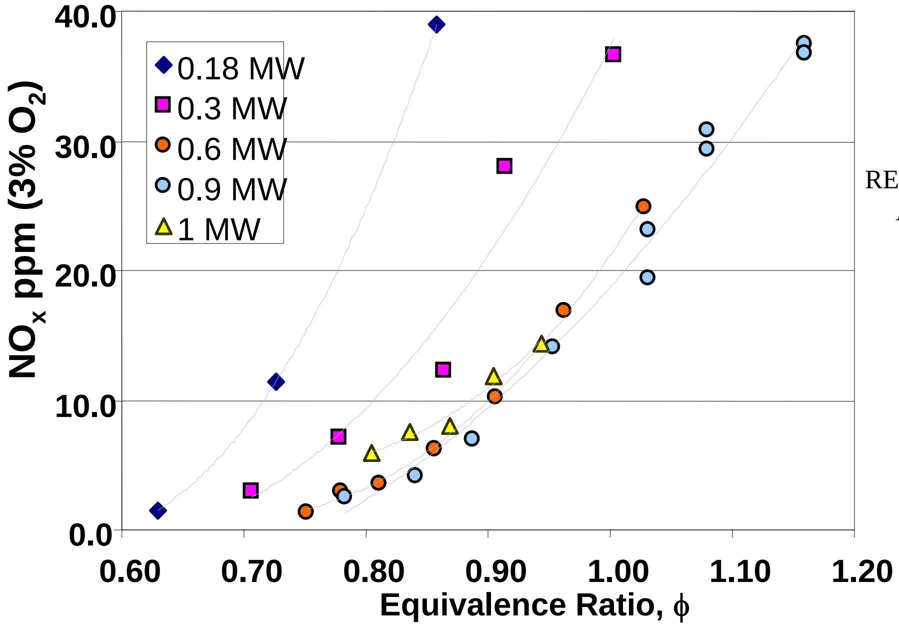
- This 2” LSB is made of PVC pipes to demonstrate lack of significant heat conduction upstream
- Flame shape identical to air-swirler flame
- Swirler has eight angled guide vanes and a large center channel (78 % burner raduis)

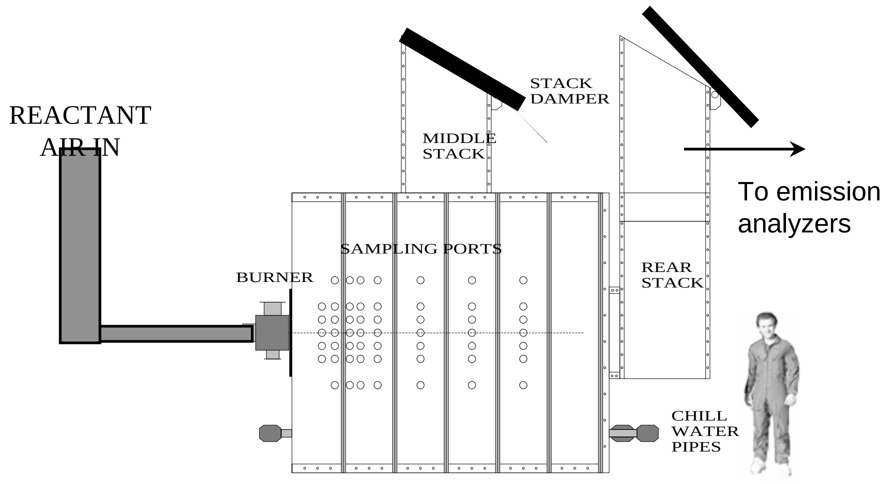
Adaptation to Industrial Heating

Scaling to Industrial Sizes

- *Scientific approach for "smart" adaptation to a broad range of process heat and boiler applications*
  - **Targeting 300 KBtu/hr to 30 MMBtu/hr burners**
- *Establish scaling rules*
  - **Exploit scientific background for low-swirl flows**
  - **Apply theory on turbulent flame speed to predict blowout/flashback**
  - **Evaluate trade-off/benefit between two scaling approaches**
    - **Higher flow velocity vs larger burner diameter**
  - **Optimize burner to fit chamber geometry**

Obtained Scaling Information Through Laboratory Experiments



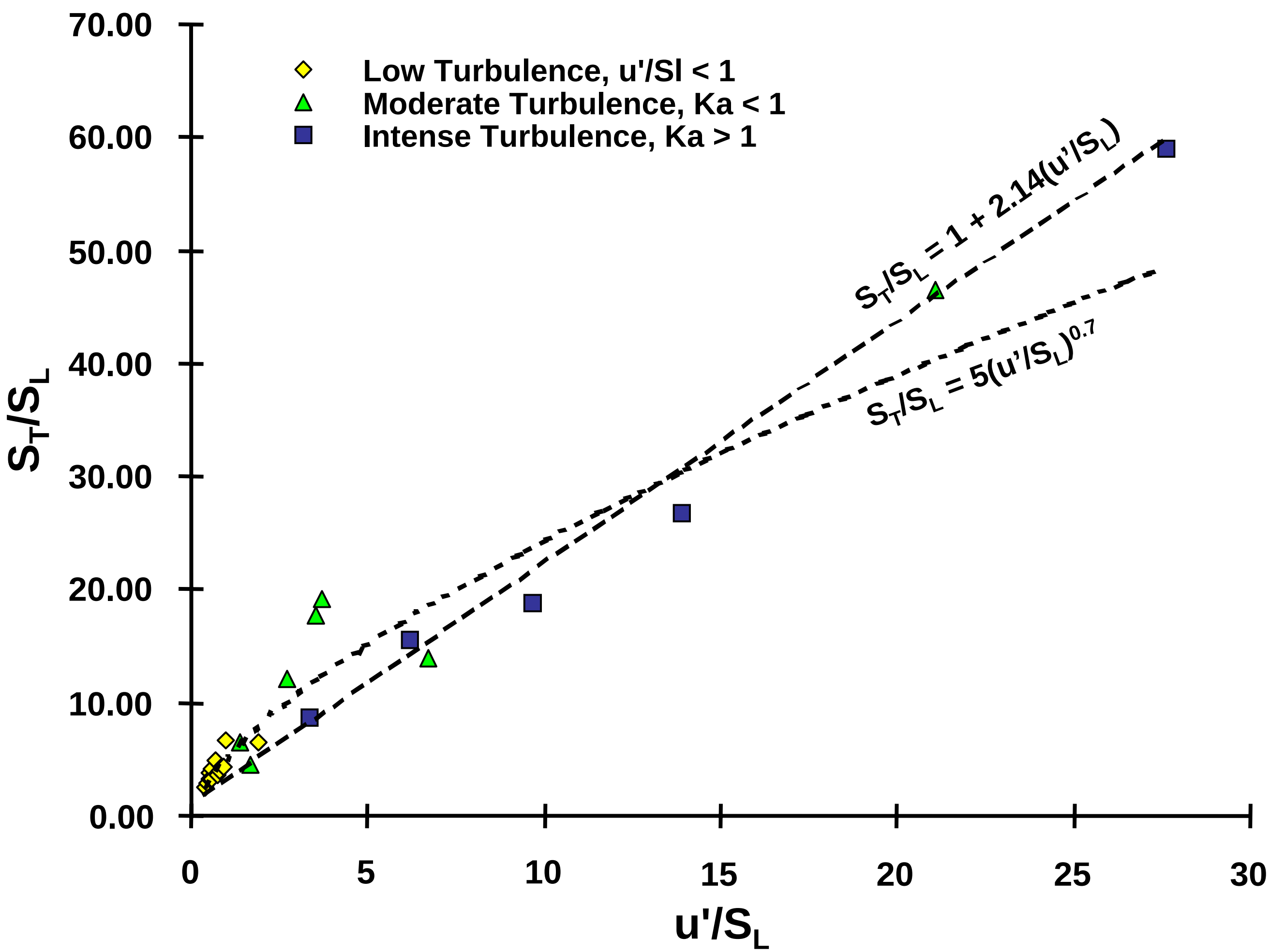


- **Comparing LSBs of different sizes (2 – 5") in furnace and boiler simulators with and without FGR (Partnering with CMC Eng., UCI, Maxon, TIAX, Zink and Aqua-Chem)**
  - **Vane shape, screen placement and small changes in swirl number have little effects on flame noise, flame stability, & lean blow off**
  - **NO_x emissions depend primarily on air/fuel ratio**
  - **Observed 30:1 turndown**

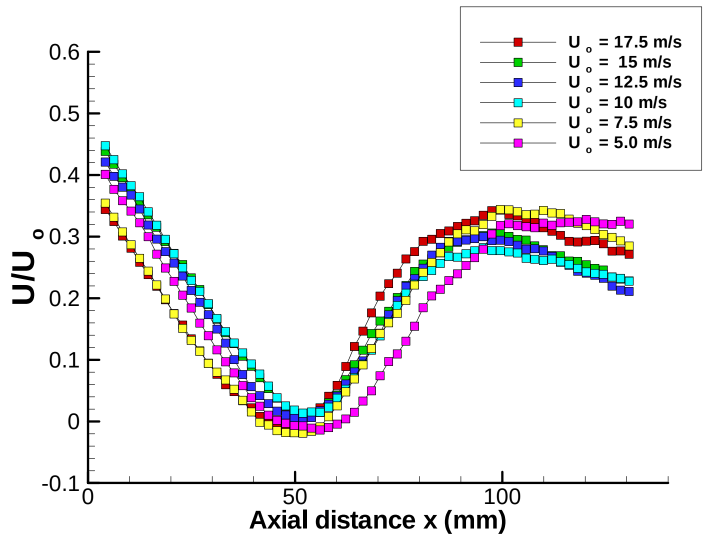
Laser Experiments Provided Scientific Explanation for LSB's Robust Performance

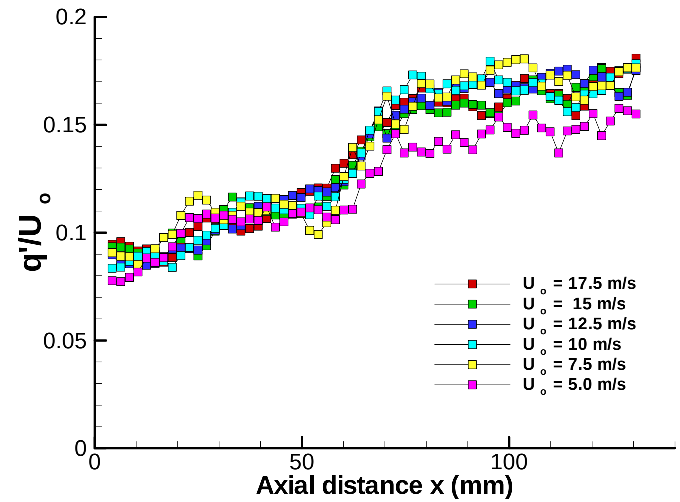
- Analyses drawn upon the theories on
  - **Turbulence scaling, production, and dissipation**
  - **Flame temperature, flame speed and reaction chemistry**
  - **Combustion aerodynamics**
- Found LSB generates self-similar flowfield
  - **Flow divergence constant in non-dimensional space**
  - **No flame shift due to linear scaling of turbulence intensity and flame speed, and weak dependence on fuel/air ratio**
- Knowledge essential for identifying, prioritizing and resolving operational issues relevant to practical applications
  - **Placement of flame ignitor**
  - **Protocol to maintain flame stability during load change**
  - **Premixing requirement**
  - **Conditioning of flow supplied to the burner**

LSB Has Very Large Turndown Because Turbulent Flame Speed Increases Linearly with Turbulence Intensity



Self-Similar Flowfield Key to Maintaining a Stationary Flame During Load Change





- **Flame position, x_f satisfies equality**

$$U_o - \frac{dU}{dx}(x_f - x_o) = S_T$$

- **Self-similarity ($dU/dx/U_o$) coupled with linearity of $S_T(u')$ and $u'(U_o)$ shows small change in x_f with U_o**

$$1 - \frac{dU}{dx}\frac{(x_f - x_o)}{U_o} = \frac{S_L(1 + Ku')}{U_o}$$

New Derivations of Swirl Number to Quantify Swirl Rates

$$S = \frac{2}{3}\tan\alpha \frac{1-R^3}{1-R^2+[m^2(1/R^2-1)^2]R^2}$$

- **New expression uses easily measurable parameters**
  - Ratio of center channel radius to burner radius, $R = R_c/R_b$
  - Straight or curved vane with angles, α
  - Ratio of mass flow rates through center channel and swirl annulus, *m*
    - Standard pressure drop procedure to obtained *m* from different screens

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Answers to Key Scaling Questions

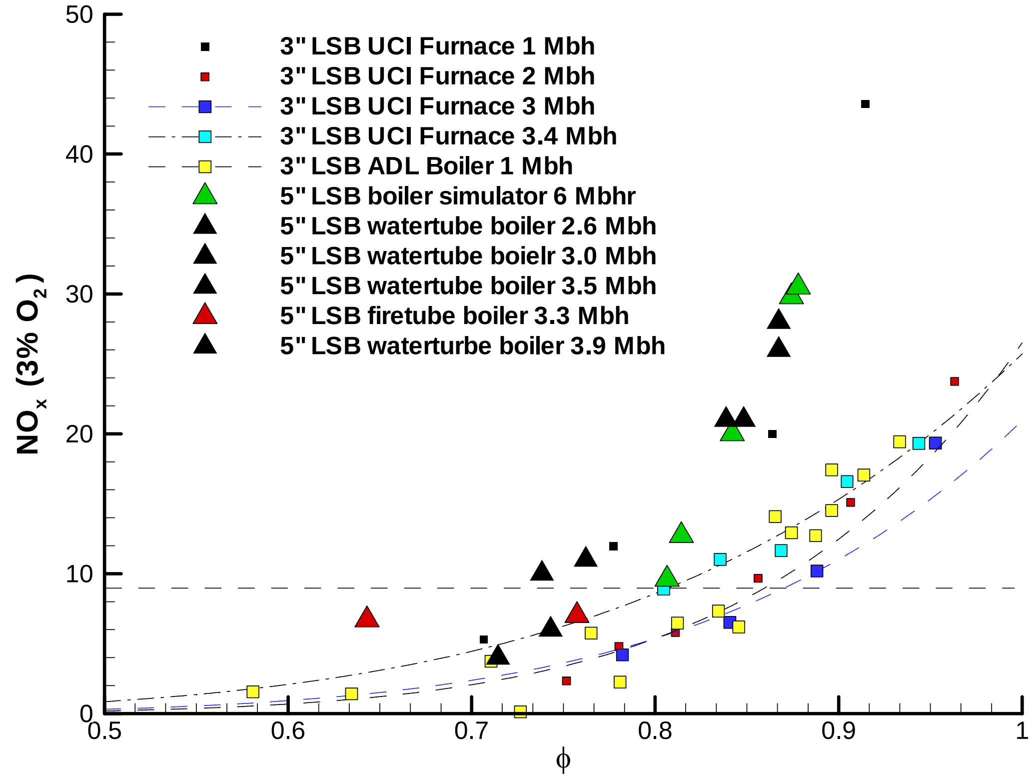
- What are the critical roles of LSB components on its operation?
  - **Size of center channel?** **Controls back pressure**
  - **Exit tube length?** **Minimum length needed for proper operation**
  - **Vane angle?** **Flame discharge angle**
  - **Vane length?** **Improves turndown but can increase back pressure**
  - **Screen placement position?** **Upstream placement preferred**
  - **Screen type?** **Not critical**
- How high we can push the velocities (thus power output)?
  - **Do we need to adjust swirl to accommodate flame shift?** **No**
  - **Will the flame blows out at high throughput?** **Not observed yet**
  - **How does the aerodynamic flowfield evolve at high velocities?** **Remains self-similar**
- How much can we increase the burner diameter?
  - **Will increase burner diameter affect flame stability range and thus swirl requirement?** **Not observed yet**
- Is there a convenient scaling rule that engineers can use? YES!

LSB Scaling & Engineering Rules

- Keep swirl recess at 1 to 1.5 diameter
- Apply 0.4 < S < 0.55 criterion
  - **Center-channel/burner ratio 0.5 < R < 0.6**
    - **Larger R increase drag thus blower power**
  - **Vane angle between 37^0 to 45^0**
    - **Vane can be curved or straight**
    - **Overlapping vanes increase turndown**
  - **Optimize burner by using different screens to change S**
    - **Screen geometry is not critical**
    - **Larger openings reduce clogging**
    - **Other options available to change** *m*
- Constant velocity scaling for power output
  - **Output power scaled by the square of the burner diameter**
  - **Minimum operating conditions at bulk flow of 10 ft/s**
- Optimum flame closure at 3 to 4 R_b
  - **Mitigation of corner recirculation zone reduces noise & vibration**

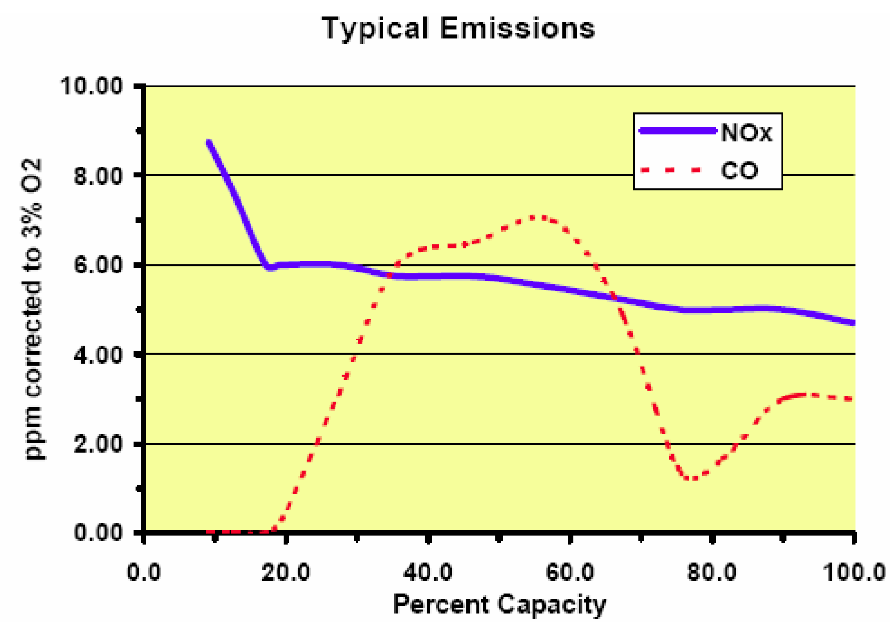
Applied 0.4 < S < 0.55 Criterion to Scale LSB up to 16” and 25 MMBtu/hr

- NO_x correlates primarily with air/fuel ratio
- LSB flames remain quiet and stable under ultra-lean and highly diluted conditions



Commercialized for Process Heat

- **Maxon Corporation licensed LSB in 2002**
- **Targeting ultra-low NO_x market (< 9 ppm at 3% O_2 guaranteed) for industrial heating, baking and drying**
- **First product line of 1 – 6 MMBtu/hr, available since Sept. 2003**
- **10:1 turndown without pilot assistance**
- **55 units installed and SCAQMD BACT certification pending**
- **Demonstrate improvement in product quality for direct heating (paint curing & food processing)**
- **Stable operation in different chamber sizes and geometries**
- **Products up to 25 MMBtu/hr being developed targeting 20:1 turndown**

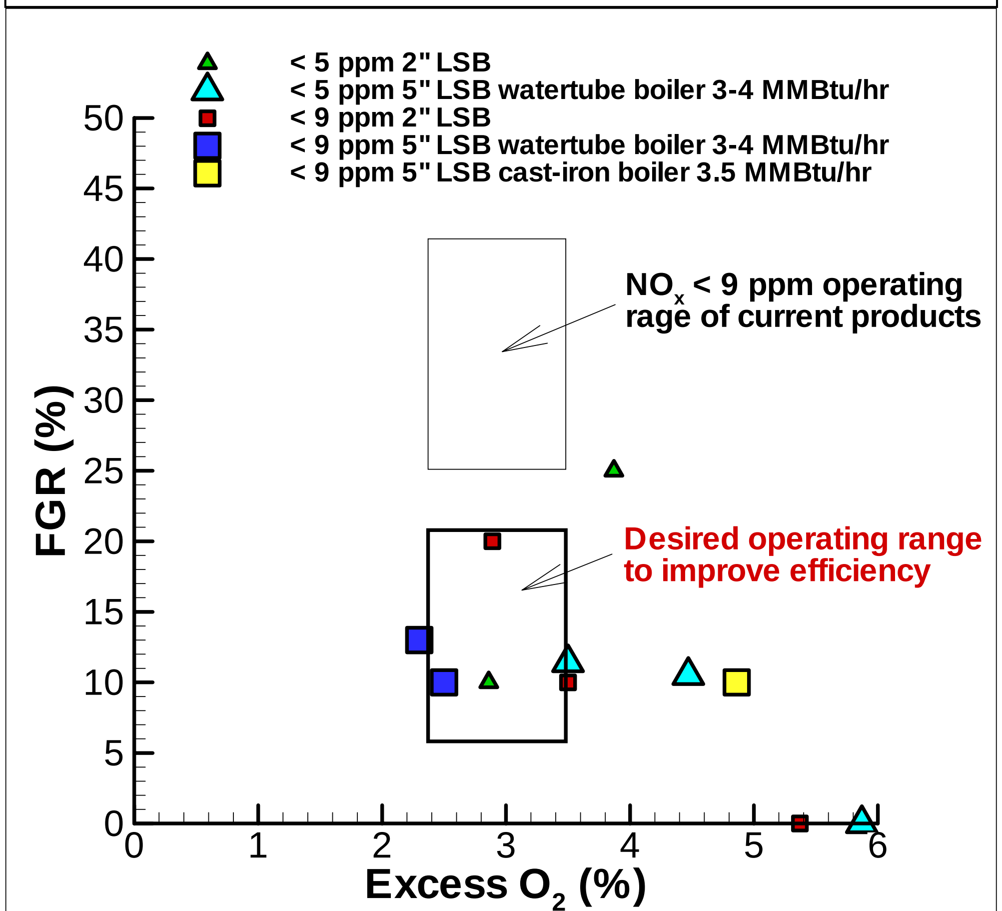


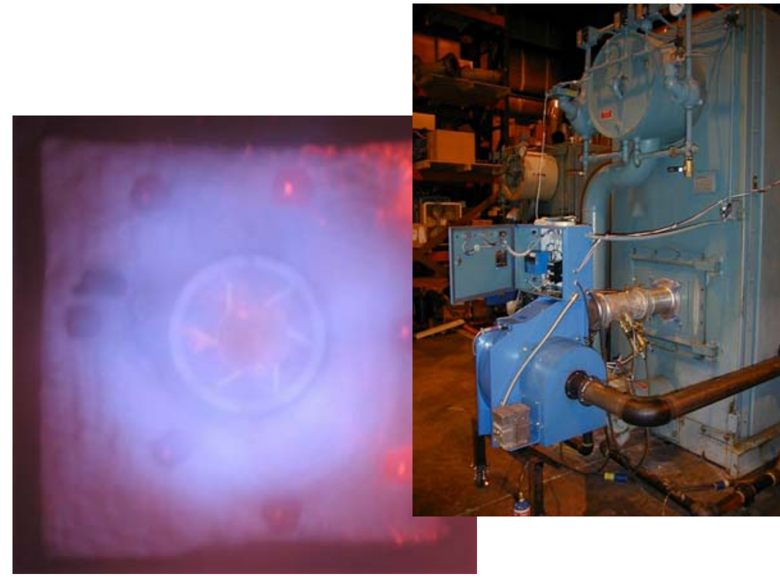
Maxon Identified Significant Economic and Technical Advantages of LSB

- Design scales by governing equations
  - A radical departure from experimentation approach
- Size compatible to existing equipment
- Can be fabricated with no initial re-tooling or new patterns required - fewer parts from common materials
- Use existing control for conventional high NO_x burners
- Flame is not in contact with burner tip
  - No thermal stresses to cause metal fatigue
- Lower operational cost, and greater ease of operation, due to a simple combustion process

LSB Tested in Commercial Watertube & Firetube Boilers with External FGR

LSB Operating points for < 9 & < 5 ppm NO_x

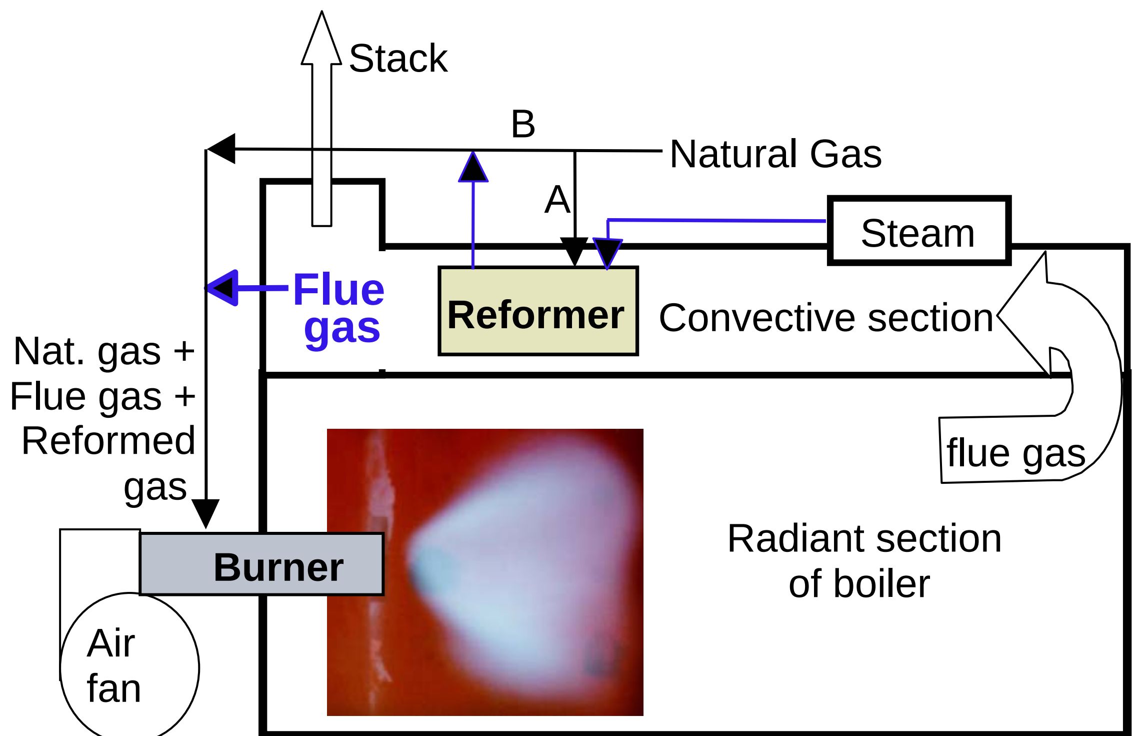




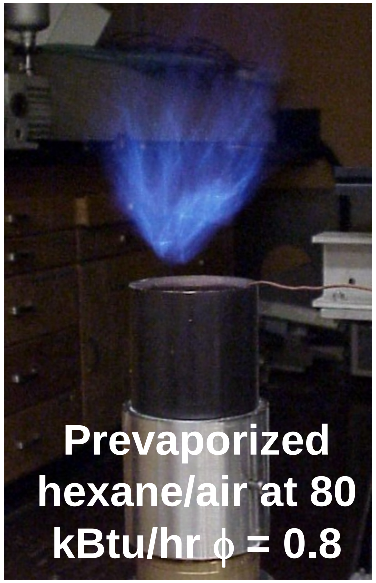
- **Use blower and controls for the commercial boiler**
- **Demonstrated low NO_x at partial load**
- **In-chamber flow pattern alters NO_x formation**
- **LSB shows good promise for improving system efficiency**

2 ppm NO_x Concept -- FGR + LSB + Partially Reformed Natural Gas (PRNG)

- Exploit combustion of hydrogen enriched natural gas
  - **Enhance flame stability & CO burnout**
  - **Use LSB to capture these benefits**
  - **Partial reformer to produce optimum H_2:CH_4 ratio in fuel**
- Laboratory development of partial reformer
- Concept verified in 50 KBtu/hr spa heater
  - **Simulated FGR and PRNG experiments**
    - **0 < FGR < 0.3**
      0 < PRNG < 0.3, 0.7 < ϕ < 0.9
  - **Actual FGR and PRNG experiments**
    - **0 < FGR < 0.3**
      0 < PRNG < 0.05 0.7 < ϕ < 0.9



Firing with Alternate Fuels



- **Liquid fuels**
  - **Laboratory prevaporized hexane premixed flame at STP**
- **Refinery Gases**
  - **Full scale testing with mixtures of natural gas, C_3H_8 and H_2**
  - **75% NG - 25% H_2**
    50% NG – 50% C_3H_8 – 25% H_2
    50% NG – 50% H_2
- **Pure H_2 & C_3H_8**
  - **Laboratory studies to investigate contribution of flame front instabilities**

Adaptation to Gas Turbines

Low-Swirl Combustion for Gas Turbines

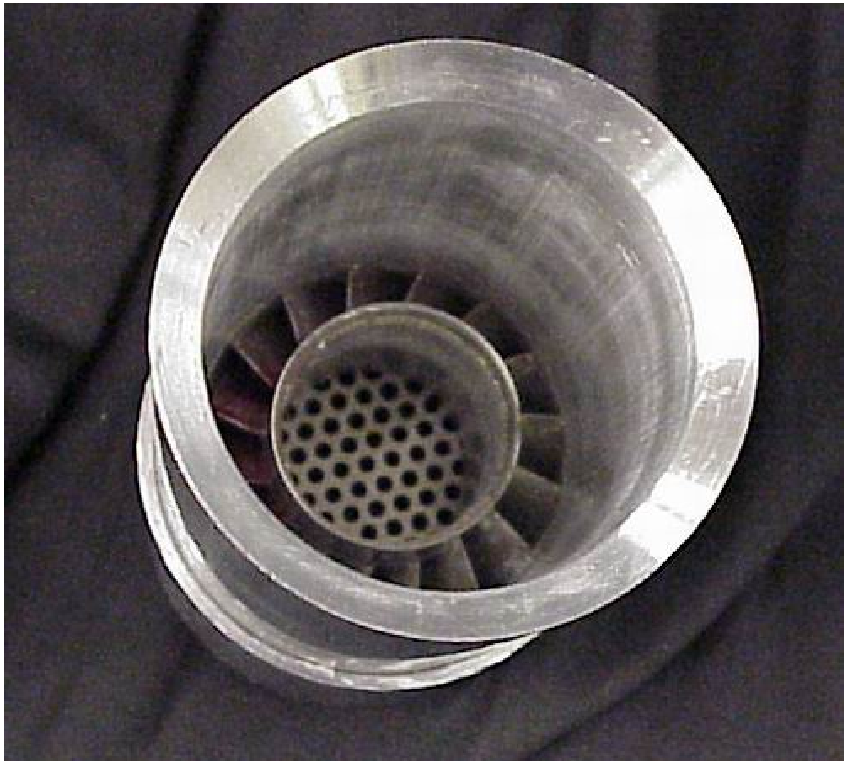
- Stationary land turbines are first to adapt lean premixed combustion to reduce NO_x
- New air-quality regulations in California and many parts of US require < 5 ppm NO_x (@15% O_2) by 2005
  - DOE-DER supporting research projects on catalytic combustors and surface stabilized combustors
    - Expensive materials that may degrade overtime
    - Elaborate controls needed to maintain smooth operation
- DOE-DER sponsoring research to develop low-swirl injector (LSI) for 5 to 7 MW engines
  - Low cost engine friendly design using existing hardware if possible

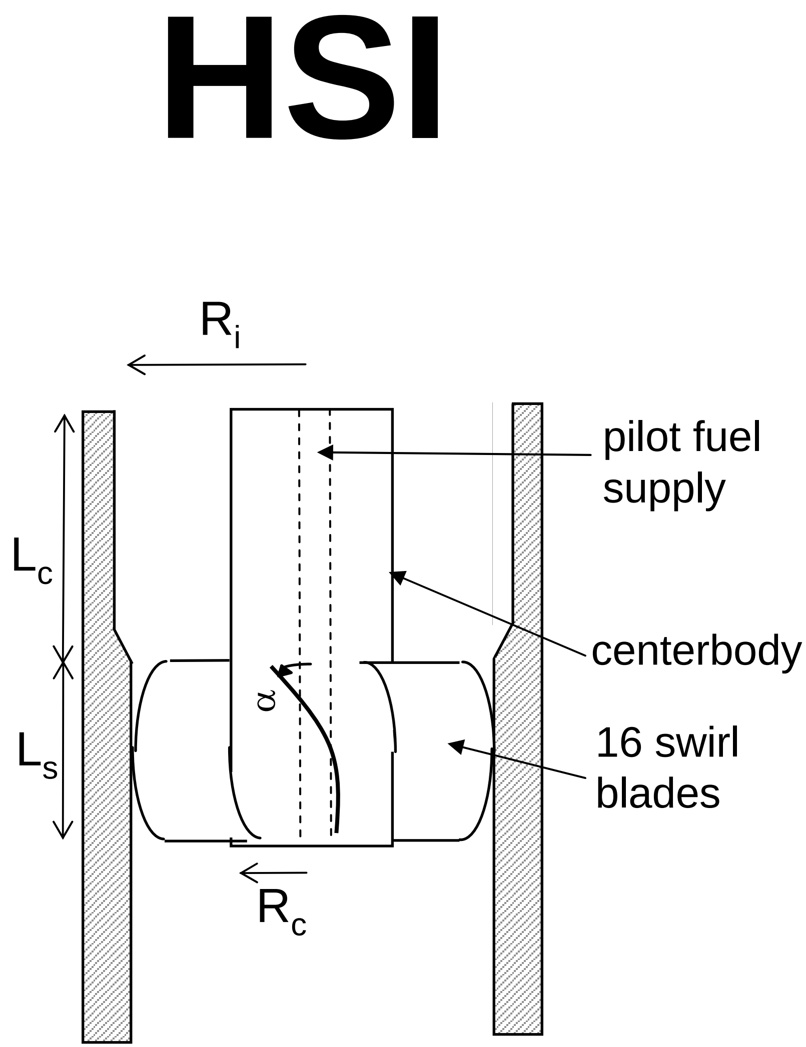
SoLoNOx High-Swirl Injector (HSI)

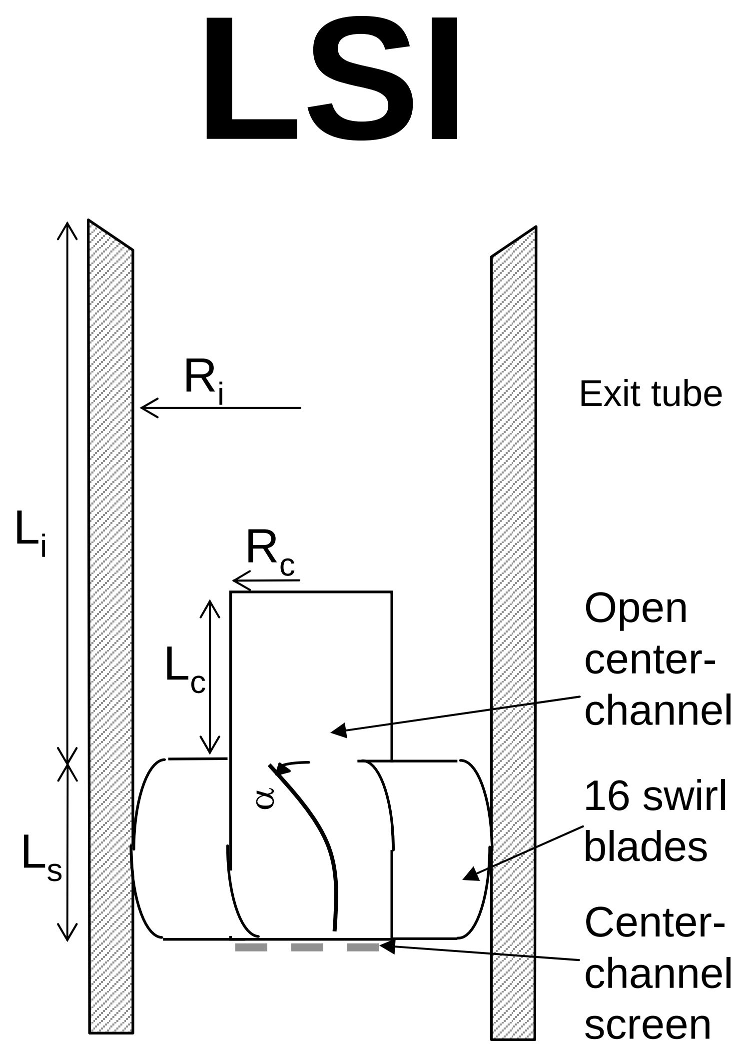
- A production part for Solar Turbines' 5 – 7 MW engines
- 6.4 cm ID with a 4 cm OD centerbody 16 curved blades with exit angle $\alpha \approx 40^o$
- Flame attachment at bluff body rim

Converted SoLoNOx HSI Into LSI

- **Followed the engineering approach for burners**
  - **Removed centerbody from SoLoNOx swirler**
  - **Fitted with an exit tube (9.5 cm) and center screen**
  - **Vary screens (50 – 73% blockage) to optimize at U_o = 10 m/s & STP**




HSI
R_i
L_c
L_s
α
R_c
pilot fuel supply
centerbody
16 swirl blades


LSI
L_i
R_i
R_c
L_c
L_s
α
Exit tube
Open center-channel
16 swirl blades
Center-channel screen

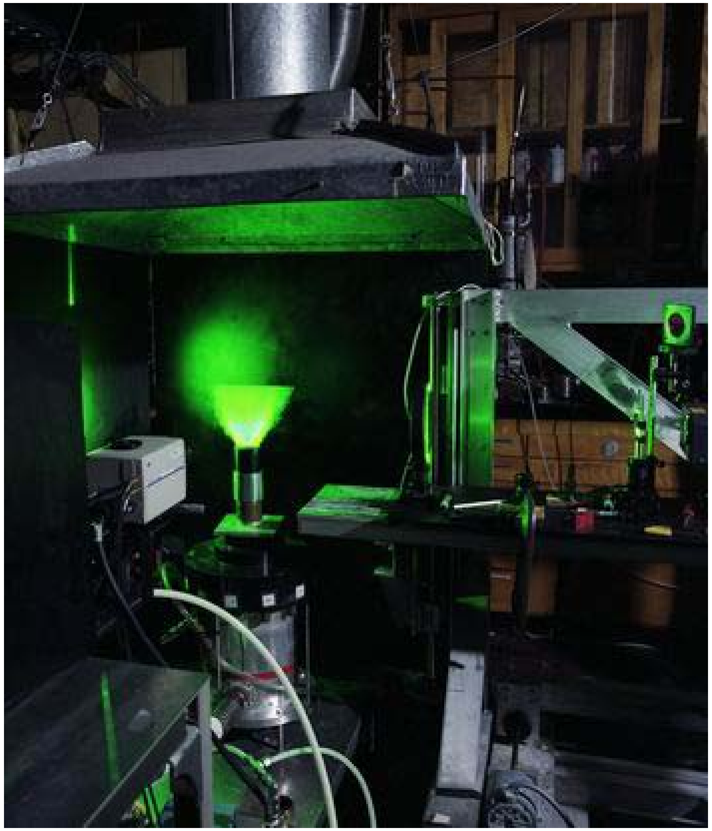
Swirl Number

$$S = \frac{2}{3}\tan\alpha \frac{1-R^3}{1-R^2+[m^2(1/R^2-1)^2]R^2}$$

- **Vane angle α = 40º**
- **Ratio of centerbody to burner radii *R_c/R_b* =** *R = 0.63*
- **centerbody/annular mass flux ratio** $\dot{m}_c / \dot{m}_a = m$

- **For LSI, *m* is controlled by screen blockage of 58% and from effective area ratio *m* = 0.3, S = 0.5**
- **For HSI, *m* = 0 and S = 0.73**

Comparison of HSI and LSI Flowfields by Particle Image Velocimetry (PIV)



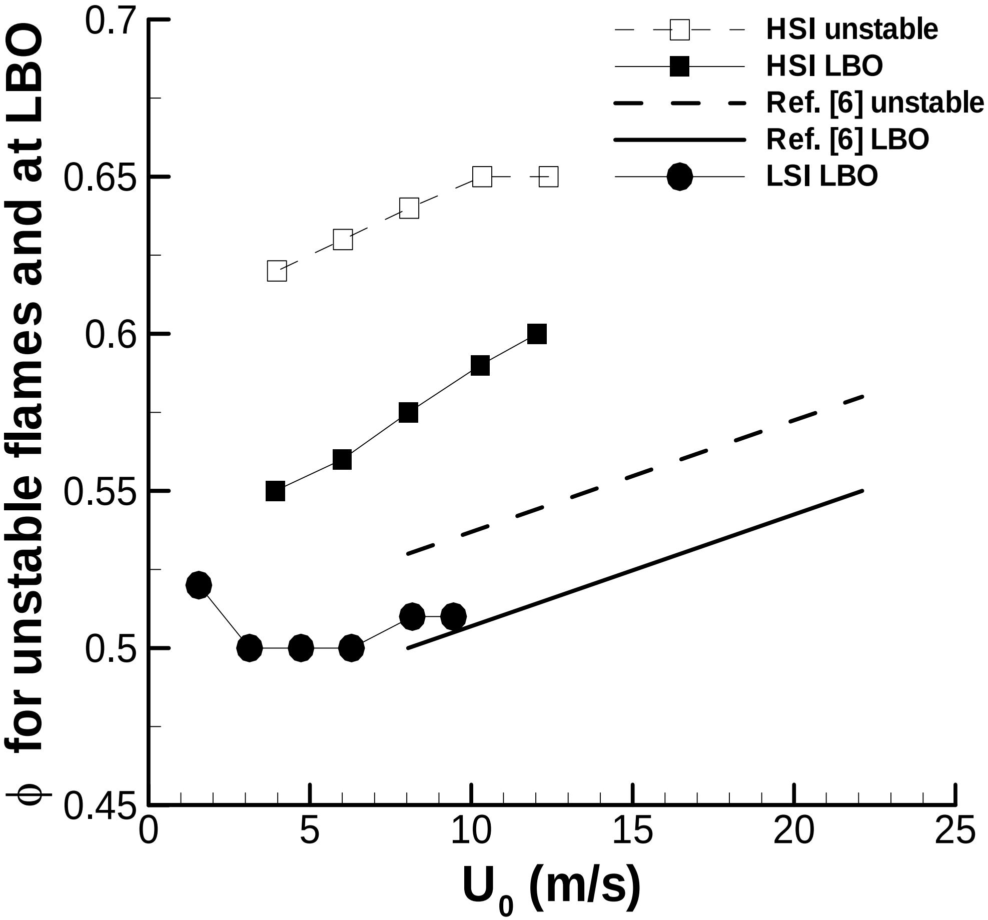
- **PIV Acquisition**
  - **New Wave Solo PIV laser double 120 mj pulses at 532 nm**
  - **Kodak ES 4.0 2000 by 2000 pixel camera**
  - **11 by 11 cm field of view 55.62 μm/pixel**
  - **Beam thickness < 1 mm**
  - **0.3 μm Al_2O_3 particles**
  - **Time separation 35 μsec**
  - **448 image pairs**
- **Analysis**
  - **64 by 64 sub-region (3.56 mm)**
  - **-3 ε rejection criterion**

Laboratory Experiments

- **All open flames using laboratory grade methane**
- **Lean blow off and instability limits determined for reactant flows of 600 to 2000 LPM**
- **PIV experiments performed at 1818 LPM with U_o = 12 m/s for HSI and U_o = 9.6 m/s for LSI**

Run	ϕ	S	Reactants Flow		U_o	Heat Release
			(LPM)	(g/s)	(m/s)	(kW)
HSI-LE0	0.0	0.73	1817	36.5	12	0.0
HSI-LE1	0.7	0.73	1816	35.3	12	76.9
HSI-LE2	0.8	0.73	1819	35.2	12	87.0
LSI-LE0	0.0	0.5	1819	36.5	9.6	0.0
LSI-LE1	0.7	0.5	1817	35.4	9.6	76.9
LSI-LE2	0.8	0.5	1814	35.1	9.6	86.8

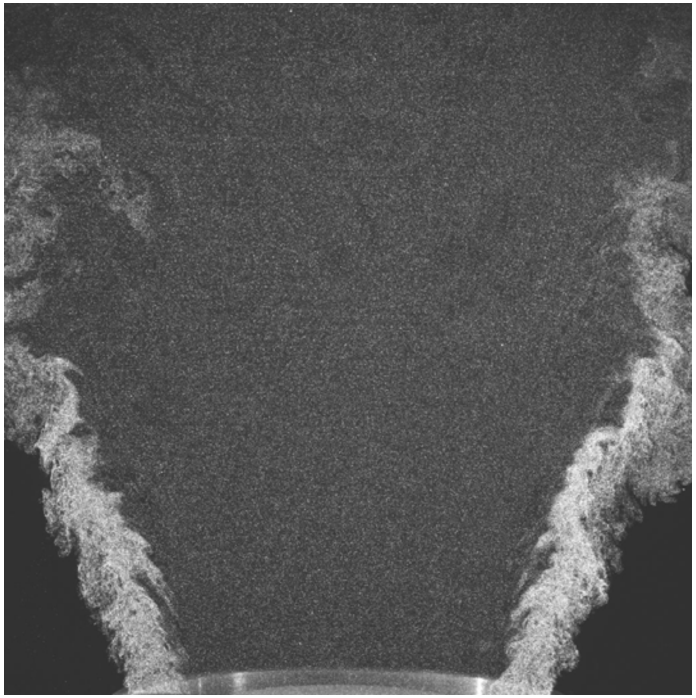
Lean Blow Off

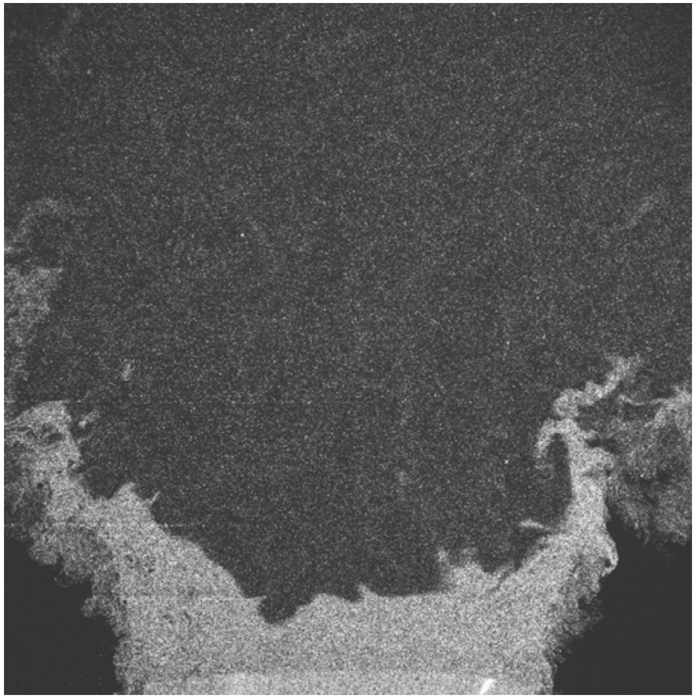


- **In HSI, intermittent flame detachment from centerbody signals flame instability preceding lean blow off**
- **Schefer et al (29th Symp) reported similar trends for HSI but at lower ϕs**
- **In LSI, flame remains stable until lean blow off at ϕ levels lower than HSI**

HSI and LSI PIV Images

- HSI and LSI have different flame wrinkle structures
- Contract between reactants and products sufficient for analysis of mean flame brush locations

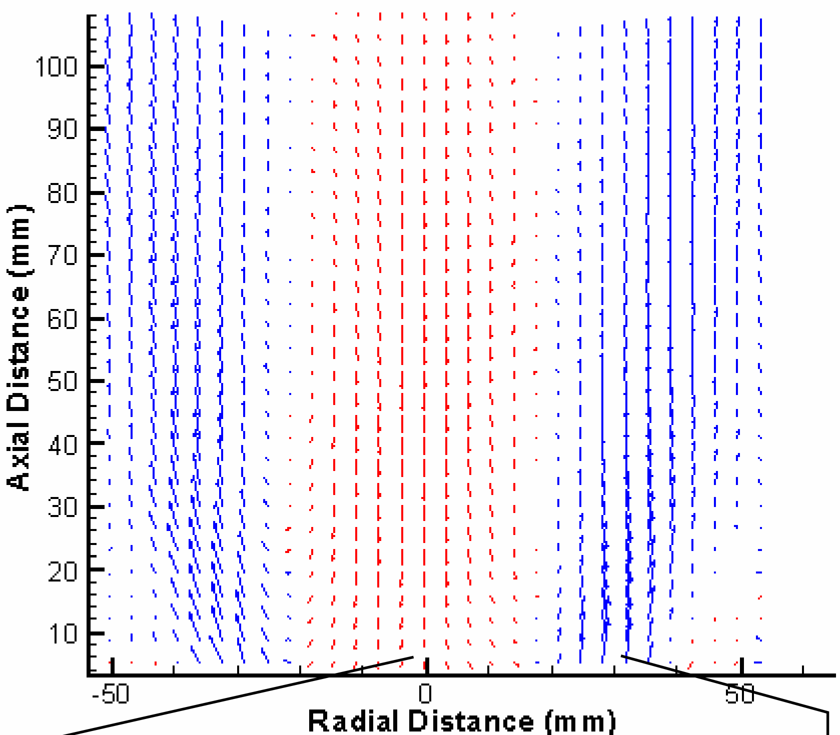




Velocity Vectors

- **HSI has a much stronger recirculation than LSI**

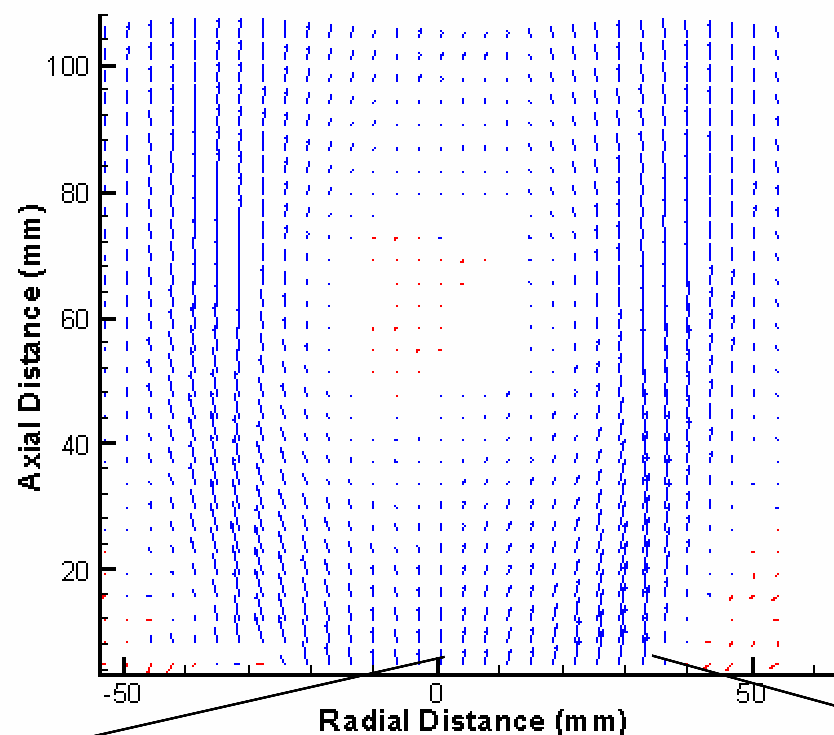
HSI Non-reacting



U = -1.8, u' = 2.0
V = 0.0, v' = 2.9

U = 16, u' = 1.9
V = 1.75, v' = 2.1

LSI Non-reacting

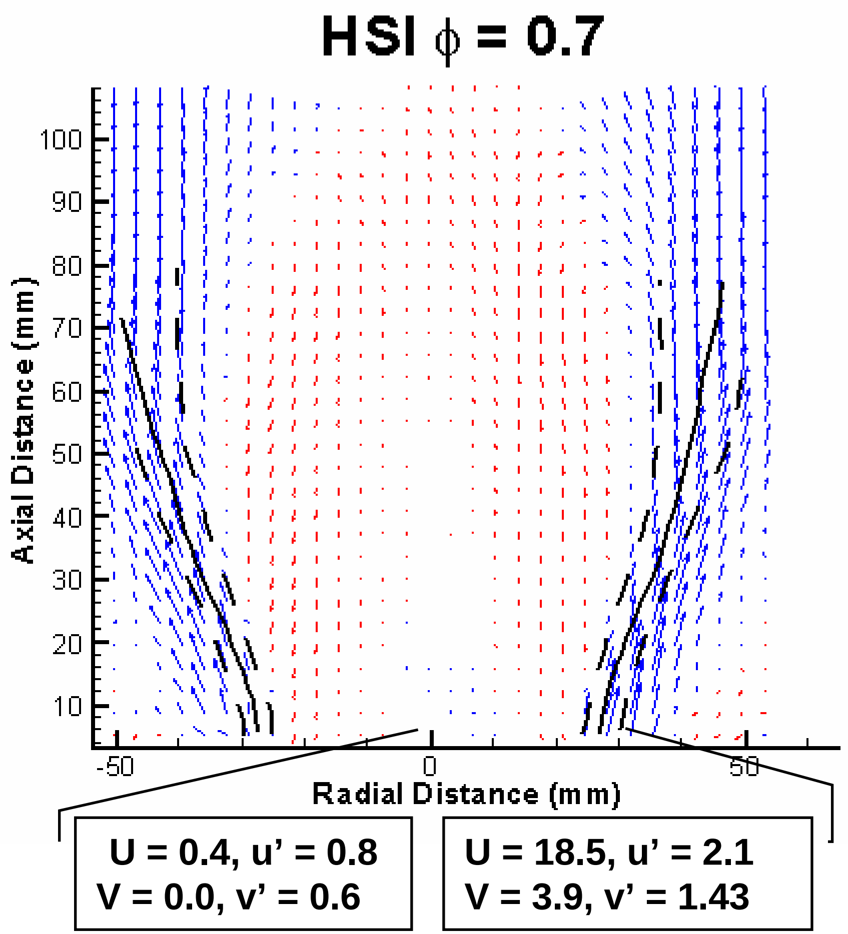


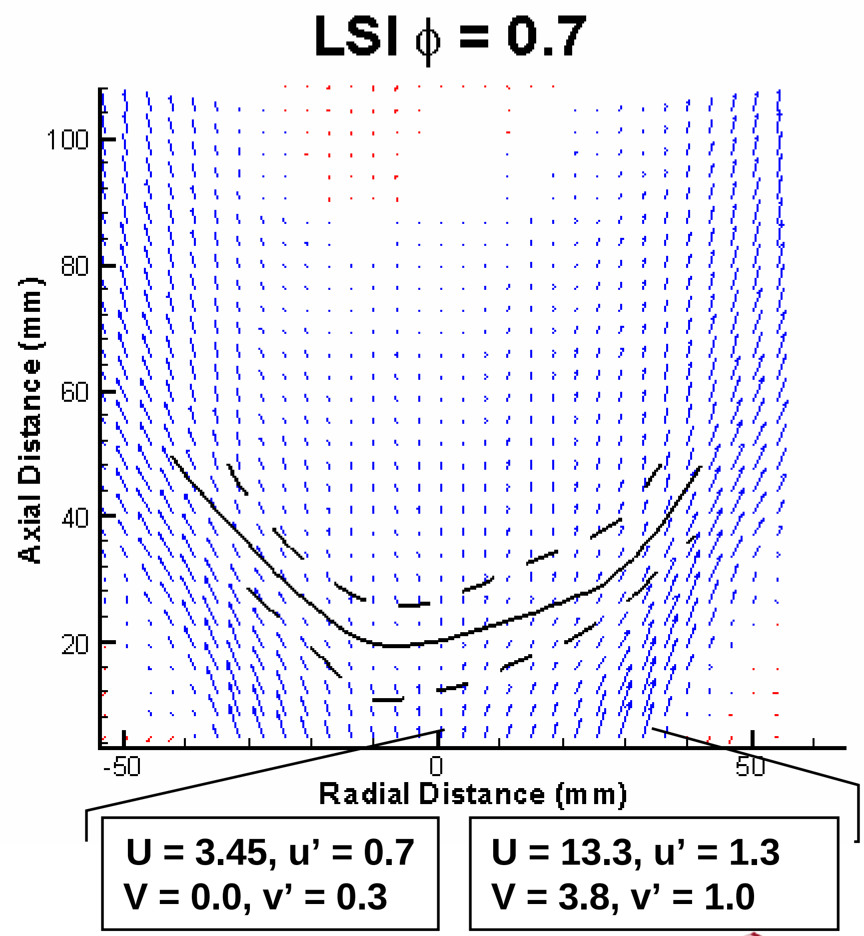
U = 4.7, u' = 0.54
V = 0.0, v' = 0.26

U = 13, u' = 1.19
V = 2.1, v' = 1.1

Velocity Vectors

- **Combustion enlarges HSI recirculation zone but pushes LSI recirculation downstream**

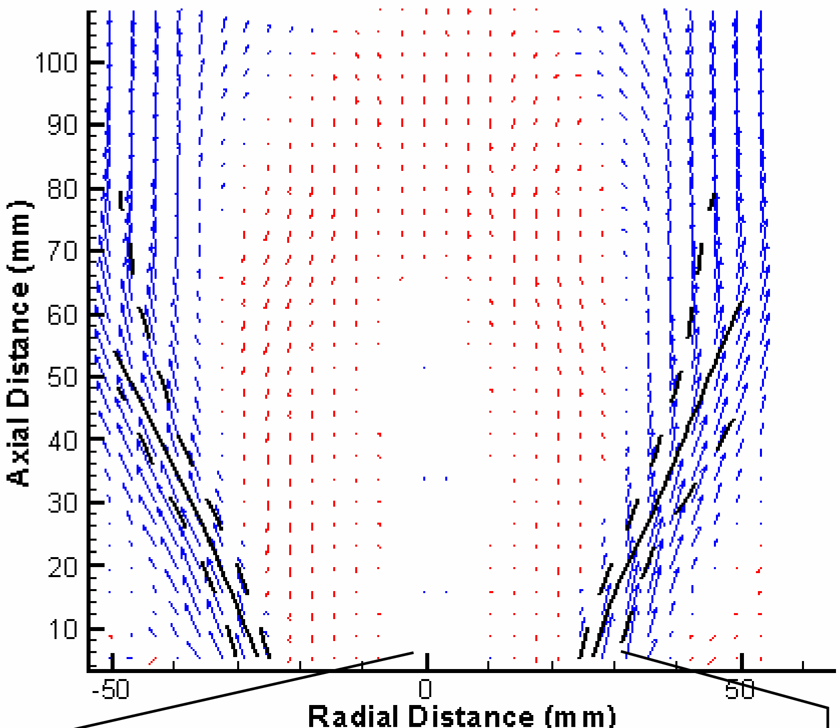




Velocity Vectors

- **Higher heat release eliminates recirculation from LSI**

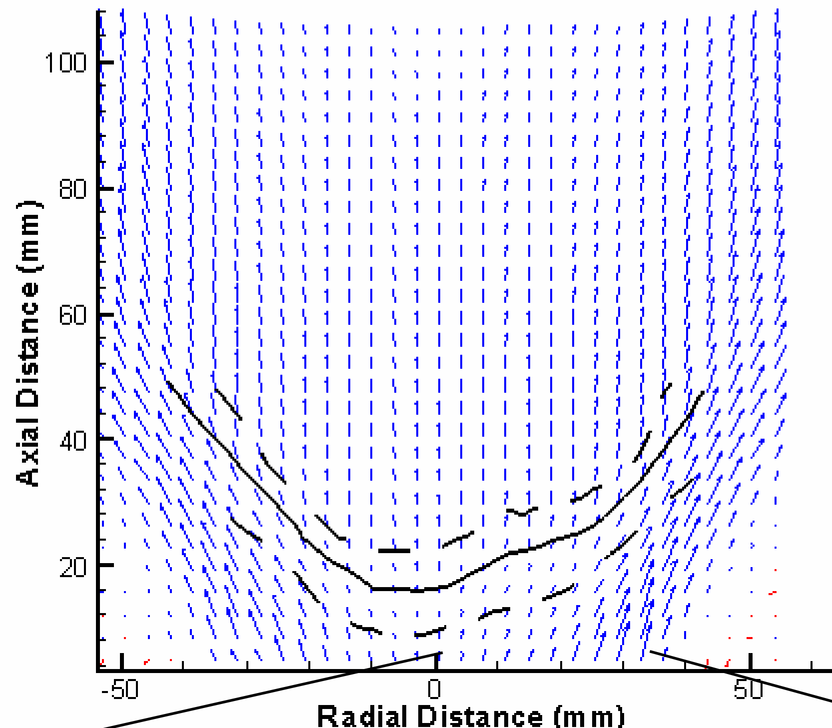
HSI ϕ = 0.8



U = 0.2, u' = 0.6
V = 0.0, v' = 1.0

U = 18.6, u' = 2.1
V = 4.0, v' = 1.6

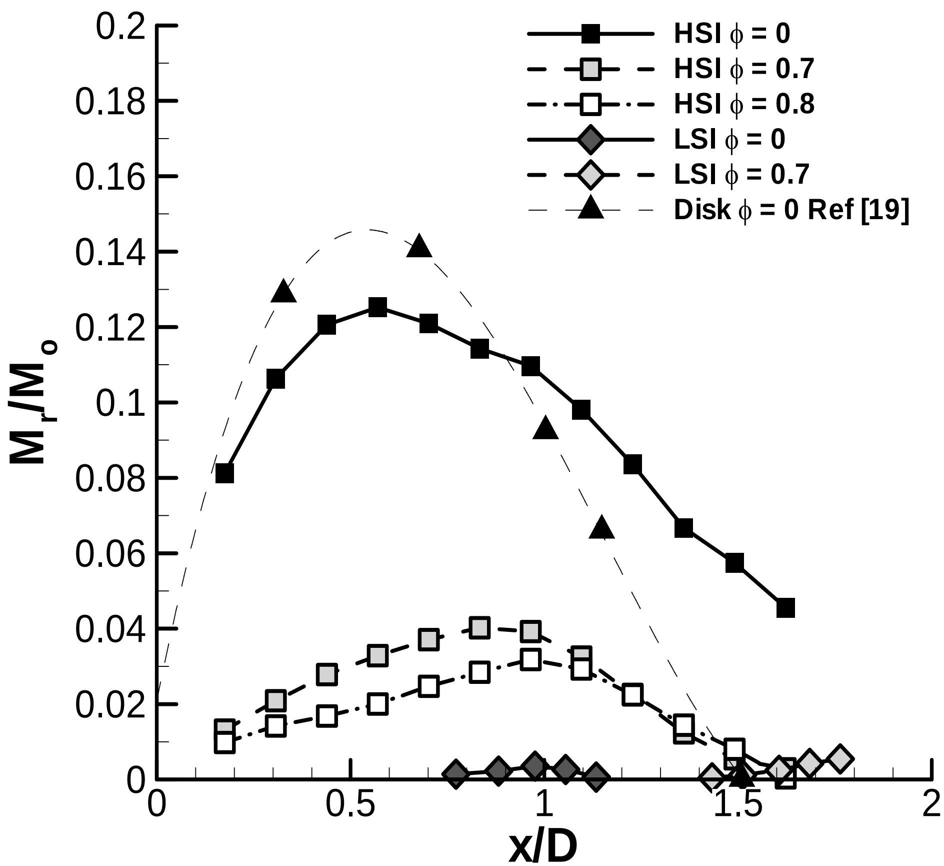
LSI ϕ = 0.8



U = 3.0, u' = 0.72
V = 0.0, v' = 0.35

U = 13.7, u' = 1.3
V = 3.8, v' = 1.0

Recirculation Zone Strength



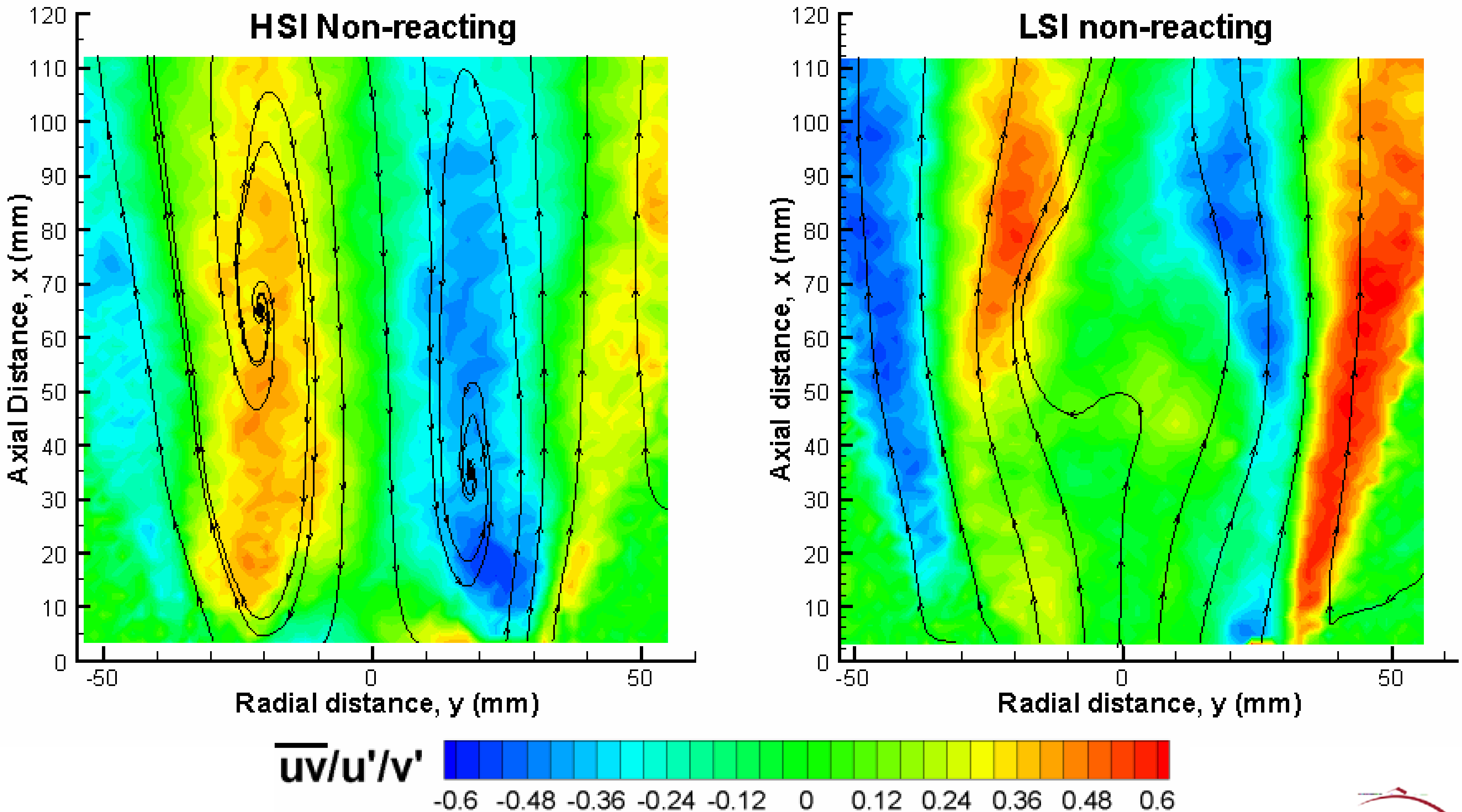
- **Reversed mass flux at a give x obtained by**

$$M_r = \int_0^{r_0} 2\pi r \rho U dr$$

for U < 0

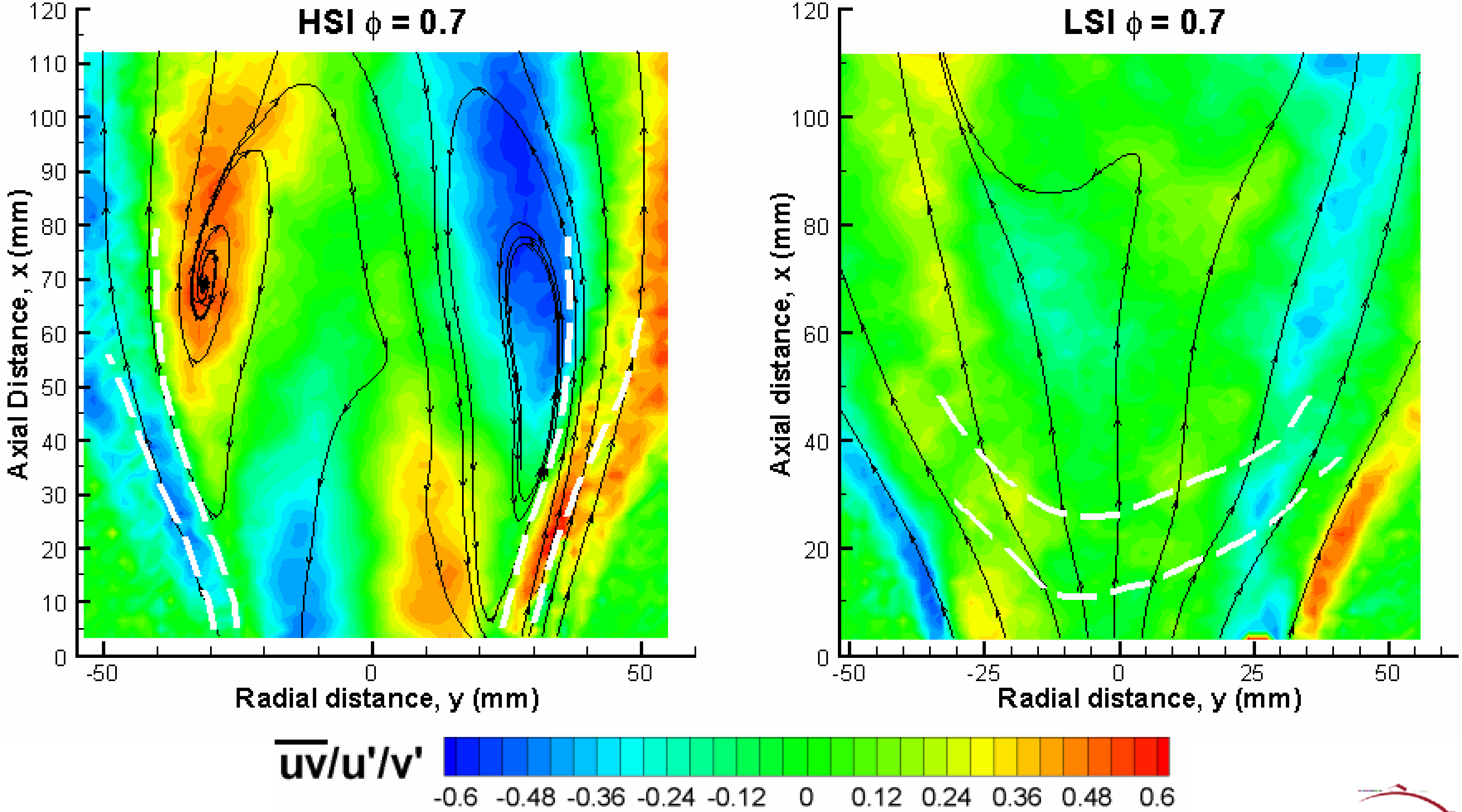
- **Assumed ρ_p/ρ_r = 0.162 and 0.15 respectively for ϕ = 0.7 and 0.8**
- **LSI flame retreated to the recirculation zone at LBO**

Normalized Shear Stress for Non-reacting flows



Normalized Shear Stress for ϕ = 0.7 Cases

- **High shear regions remain in HSI but disappear in LSI**



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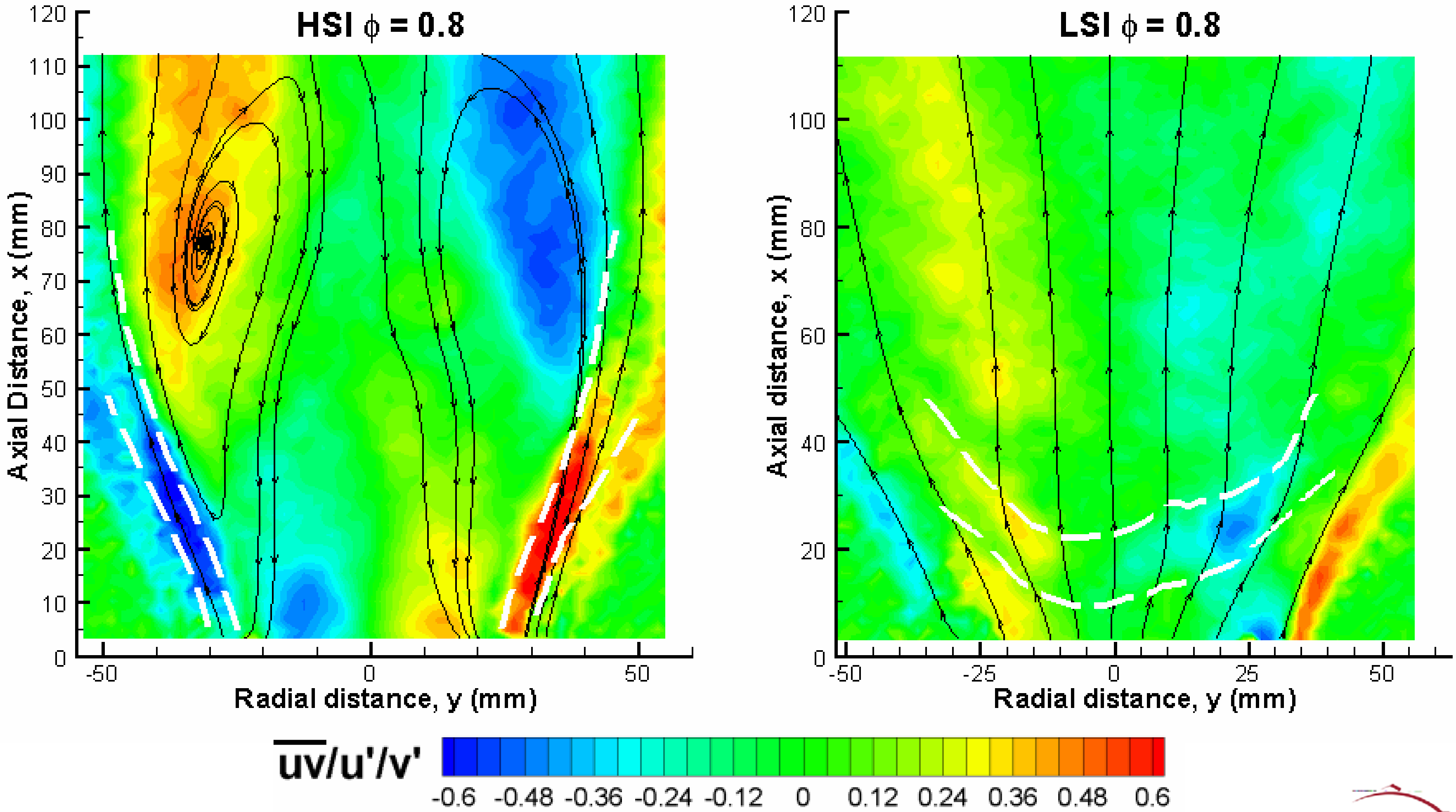
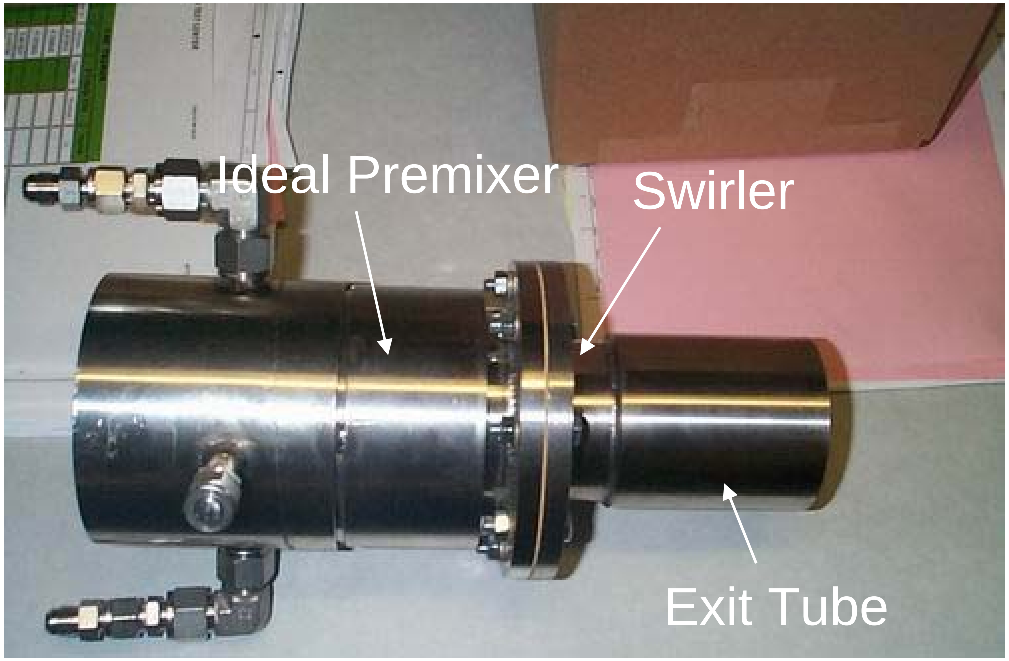
Normalized Shear Stress for ϕ = 0.8 Cases

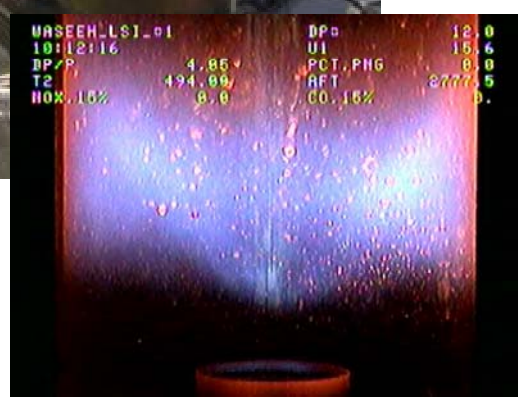


LSI for Rig Experiments



- **LSI mounted to to premixer with +/- 3% and +/- 10% homogeneity**
- **Used both premixers for experiments in Solar Turbine Quartz tube rig**
- **Used +/- 3% premixer for experiments a high pressure cell**

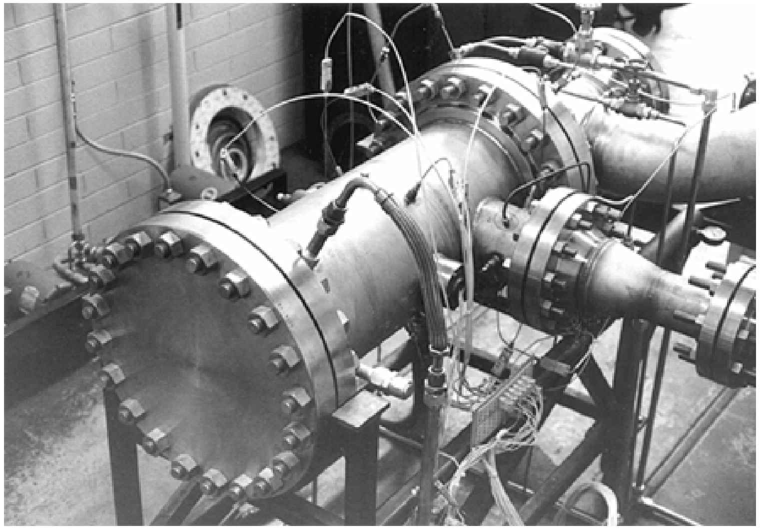
Quartz Tube Rig

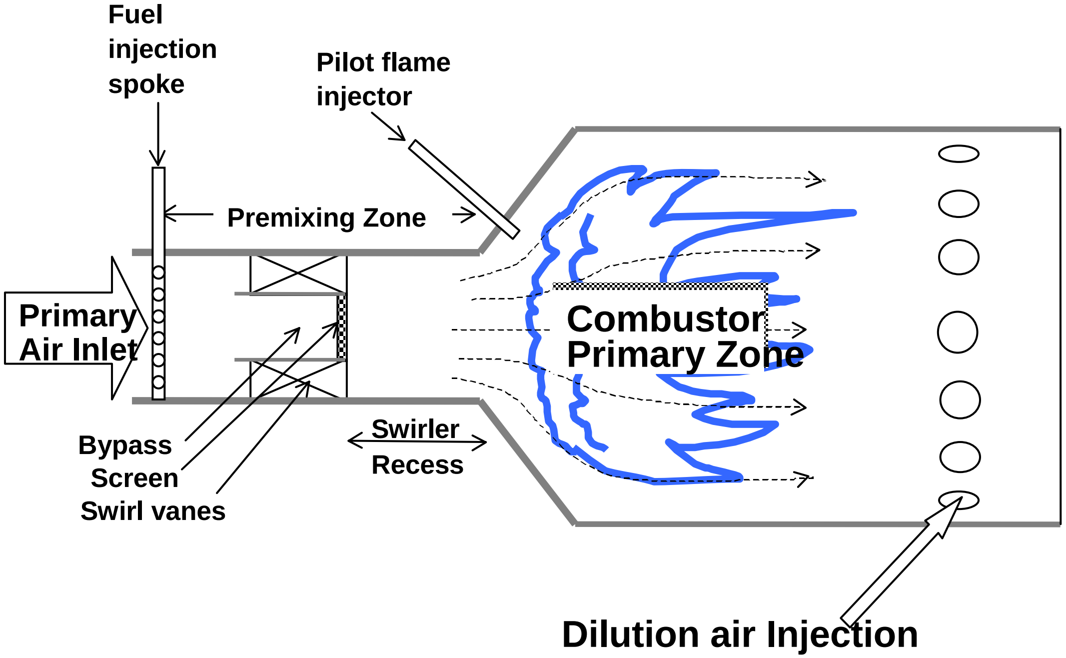


- Quartz cylinder 45 cm long 20 cm diameter simulates the enclosure of a gas turbine combustor but not its exit constriction
- LSI experiments with preheated air to examine flame liftoff and stability at U_o comparable to engine conditions
- Emission sampling probe at quartz cylinder exit

High Pressure Combustor Rig

- Simulates T_o and P_o environment in a gas turbine
- LSI and a louvered combustor liner (45.7 cm long, 20.3 cm diameter) fitted inside a horizontal stainless steel cylindrical chamber
- Emission sampling probe in cooled exhaust stream



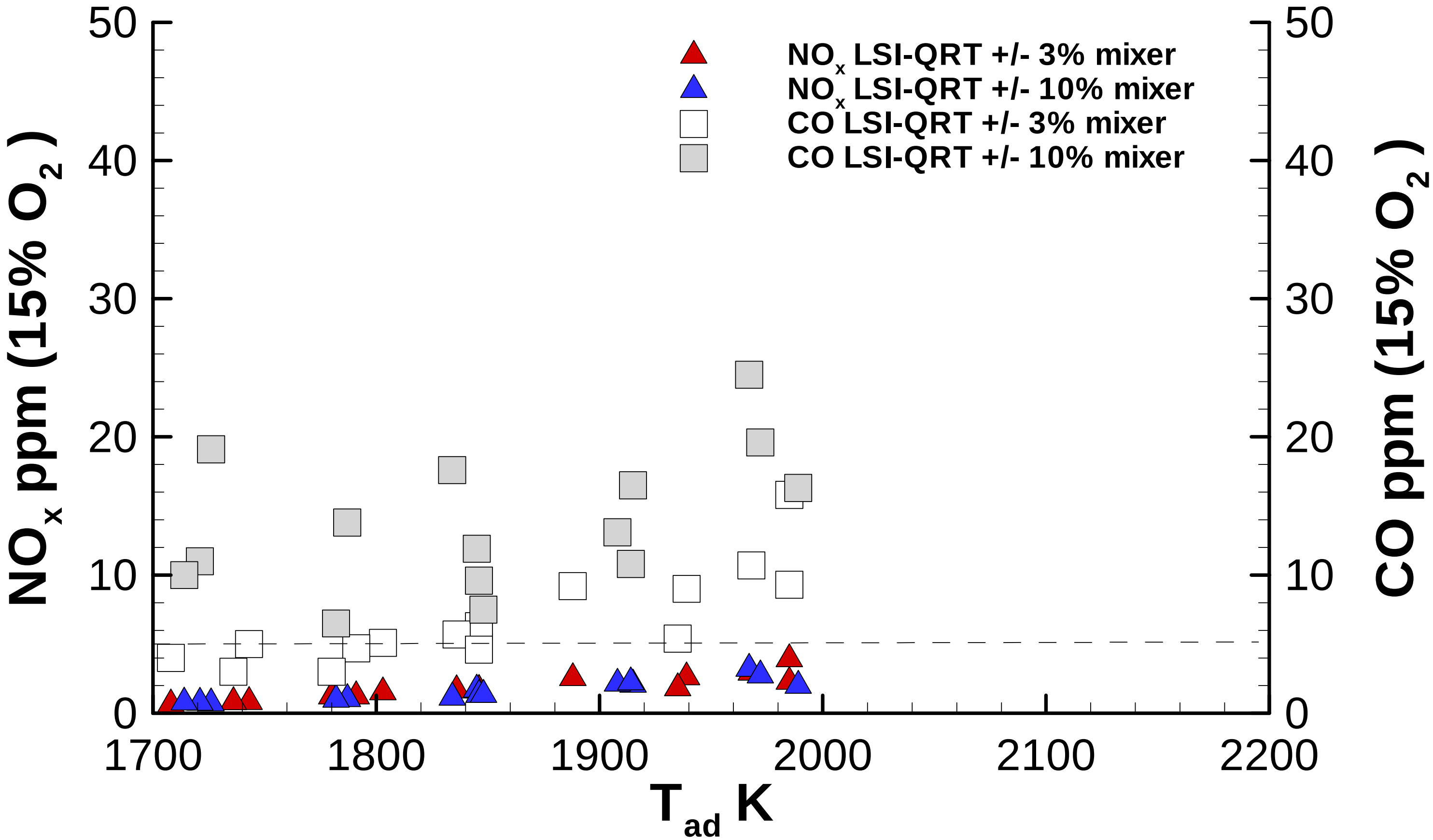


LSI & HIS Rig Experiments

Run	ϕ	Air flow (kg/s)	Fuel Flow (kg/hr)	T_0 (C)	P_0 (atm)	U_0 (m/s)	Heat Release (MW)
LSI-QR1	0.5-0.63	0.05-0.07	5.5-9.3	360-370	1	24-34	0.08-0.14
LSI-QR2	0.48-0.63	0.065-0.09	7.3-12	375-380	1	32-44	0.1-0.18
LSI-CR1	0.67-0.7	0.44-0.5	63-76	230	6	30-39	1-1.1
LSI-CR2	0.64-0.76	0.8	111-130	230	11	29-31	1.7-2.0
LSI-CR3	0.55-0.67	1-1.16	96-112	341	11	36-40	1.4-1.7
LSI-CR4	0.53-0.7	1-1.16	120-163	370	12	45-52	1.8-2.5
LSI-CR5	0.51	1.33	147	430	15	48	2.2
HSI-CR1	0.53-0.72	0.71-0.72	80-111	360	11	31-32	1.2-1.7

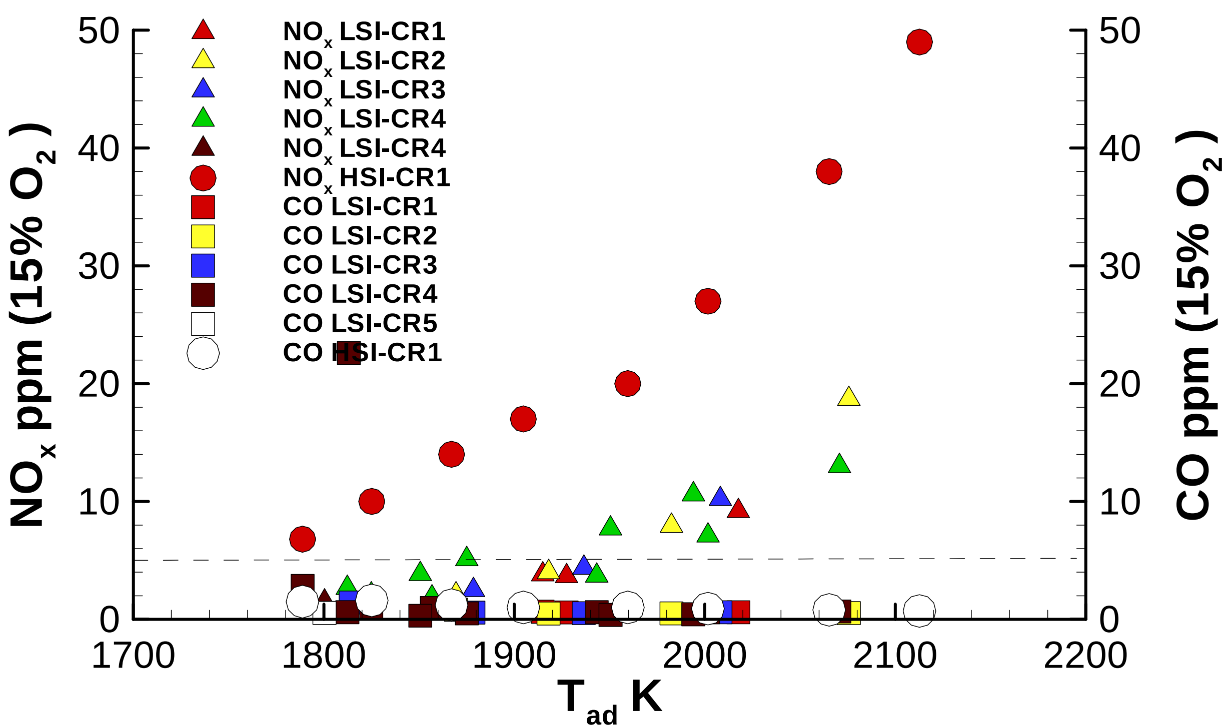
Emissions of Quartz Tube Rig Experiments

- Flame locations not sensitive to U_o and T_o
- NO_x emissions unaffected by mixture uniformity
- CO emissions slightly higher but acceptable



Emissions of Combustor Rig Experiments

- **Demonstrated validity of low-swirl flame stabilization method at gas tubine conditions**
- **NO_x emissions of LSI significantly lower then HSI**
- **CO emissions well below acceptable limit**



Attributes of LSI

- Reduce NO_x below 5 ppm without the need to operate at T_{PZ} close to lean blowoff limit
- Lower pressure drop can increase system efficiency
- No flame shift or flashback
- Flame robust to withstand large swing in inlet conditions
- Has yet to show vulnerability to oscillations
- Emissions not sensitive to degree of mixedness

Progress on Low-Swirl Injector Development

- **Demonstrated LSI concept for 5 – 7 MW engines**
- **Fabrication of LSI can exploit existing hardware**
  - **fully compatible with current engine frames**
  - **Operable with conventional premixers**
  - **very low add-on cost expected for implementation**
- **Lowest emissions of LSI match those of catalytic combustors**
  - **non-catalytic LSI does not shorten cycle time**
- **Show good promise to maintain low emission under partial load**
  - **does not required elaborate staging scheme to maintain low emissions under partial load**
- **Engine-ready prototypes designed and being fabricated**
  - **Emission targets < 9 ppm NO_x for retrofits, < 5 ppm NO_x for new engines**

Outlooks

- **Low-swirl combustion is a new platform for heating and power generation**
- **Burners**
  - **Process heat – developing enhancement methods with Maxon**
  - **Boilers & petroleum refining – continue development and commercialization with OEMs**
- **Turbines**
  - **5 – 7 MW engines – Solar Turbines will begin engine test in early 2005**
  - **Midsize, large & IGCC engines – discussion with OEMs on R&D partnerships and seeking funding opportunities**
- **Enabling Technologies**
  - **Partially reformed natural gas – seeking partnership for scale up demonstration**
  - **Alternate fuels – demonstrated with H_2, HC/H_2, biomass & low-Btu fuels.**
  - **Prevaporized premixed liquid fuels – demonstrated firing with hexane**
  - **Combine heat & power generation – LSB+LSI, burning of vitiated air**

Adaptation to Midsize, Large and IGCC Engines

- **Engineering issues**
  - **Scaling to larger sizes**
  - **Verify operation at higher T & P**
  - **Optimize for fuel flexibility**
  - **LSI/Combustor layout**
  - **Integrate with other components**
  - **Operations & Controls**
- **Fundamental Issues**
  - **Instability characteristics of LSI**
  - **Modeling & simulation**
  - **Flowfield/emission coupling**
  - **Properties of muti-fuel flames**